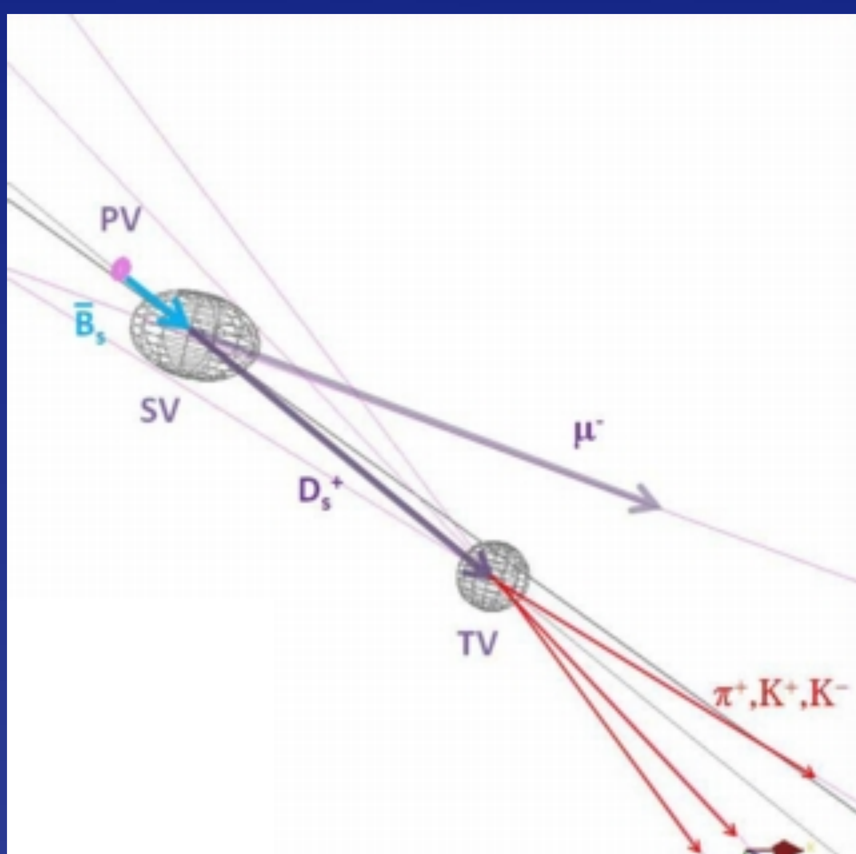
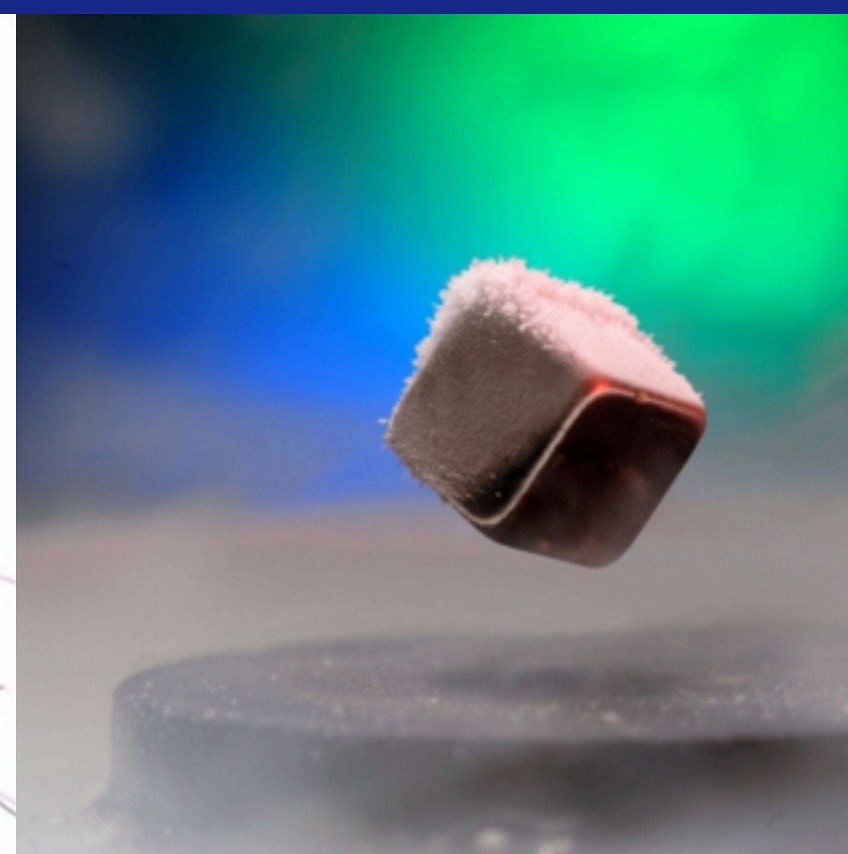
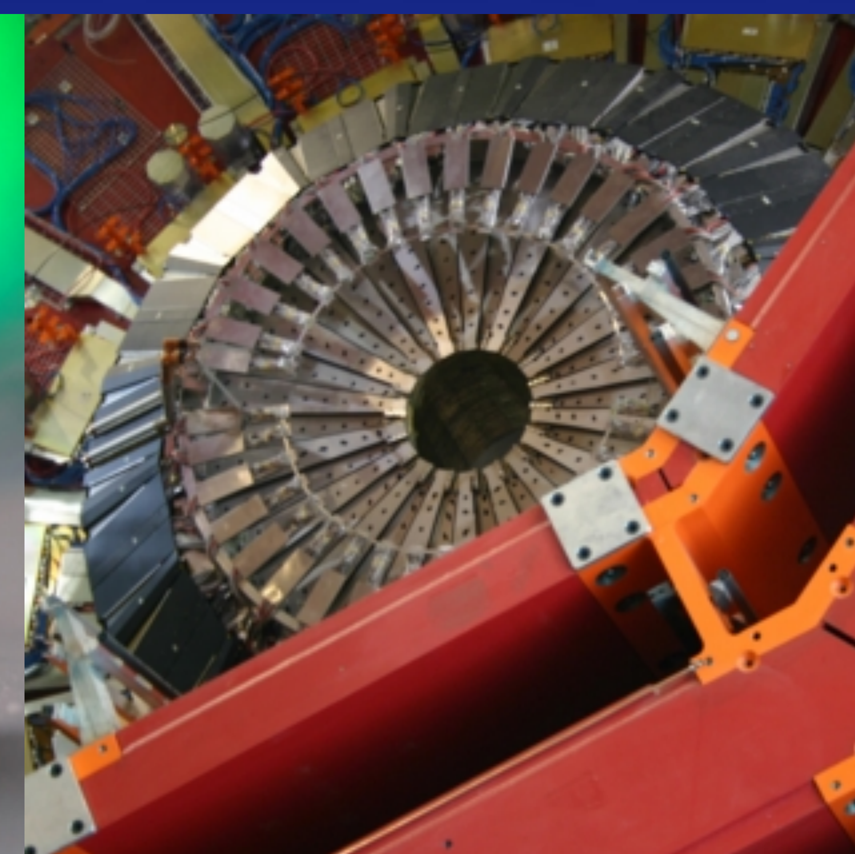
The Coming Revolutions in Particle Physics

Chris Quigg



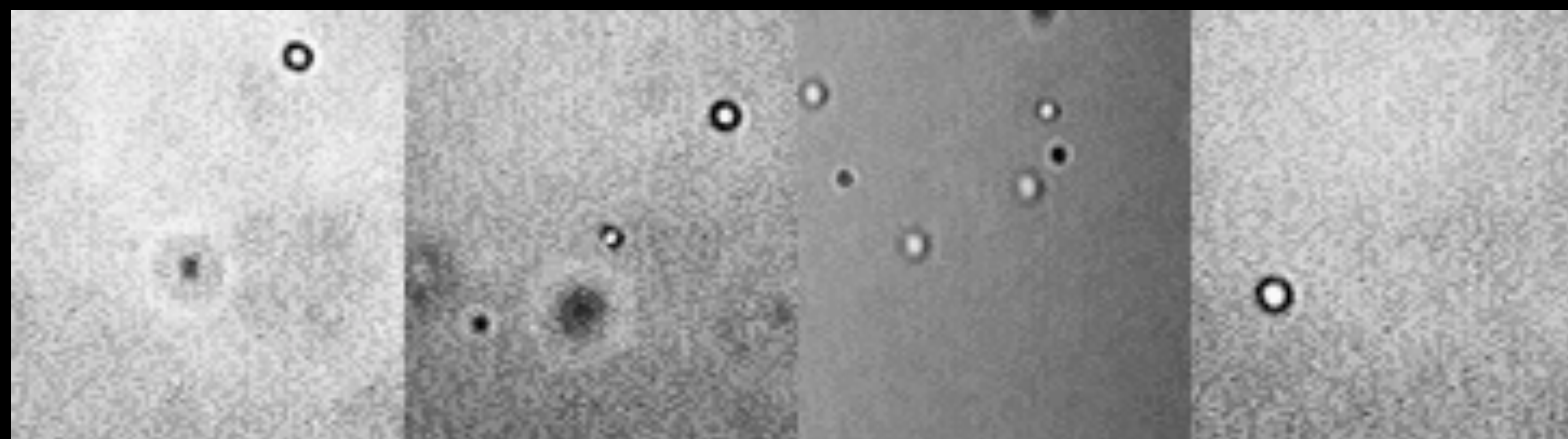




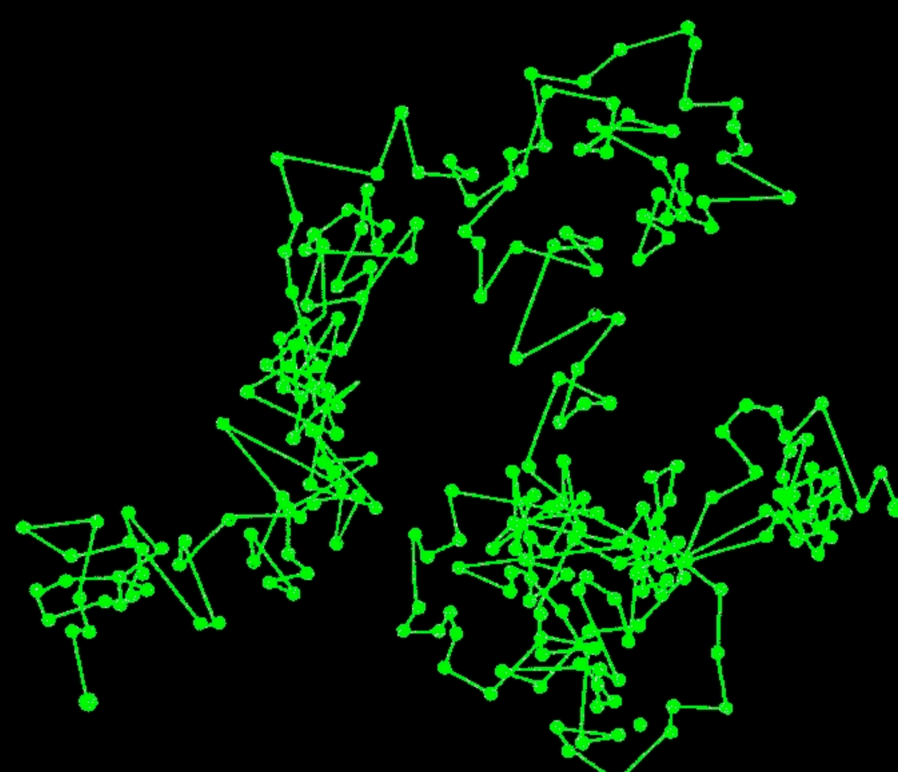
Atoms became real in the 20th century

To explain a complicated visible by a simple invisible

Jean Perrin



Eric Weeks, Emory U.



5. ***Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen;***
von A. Einstein.

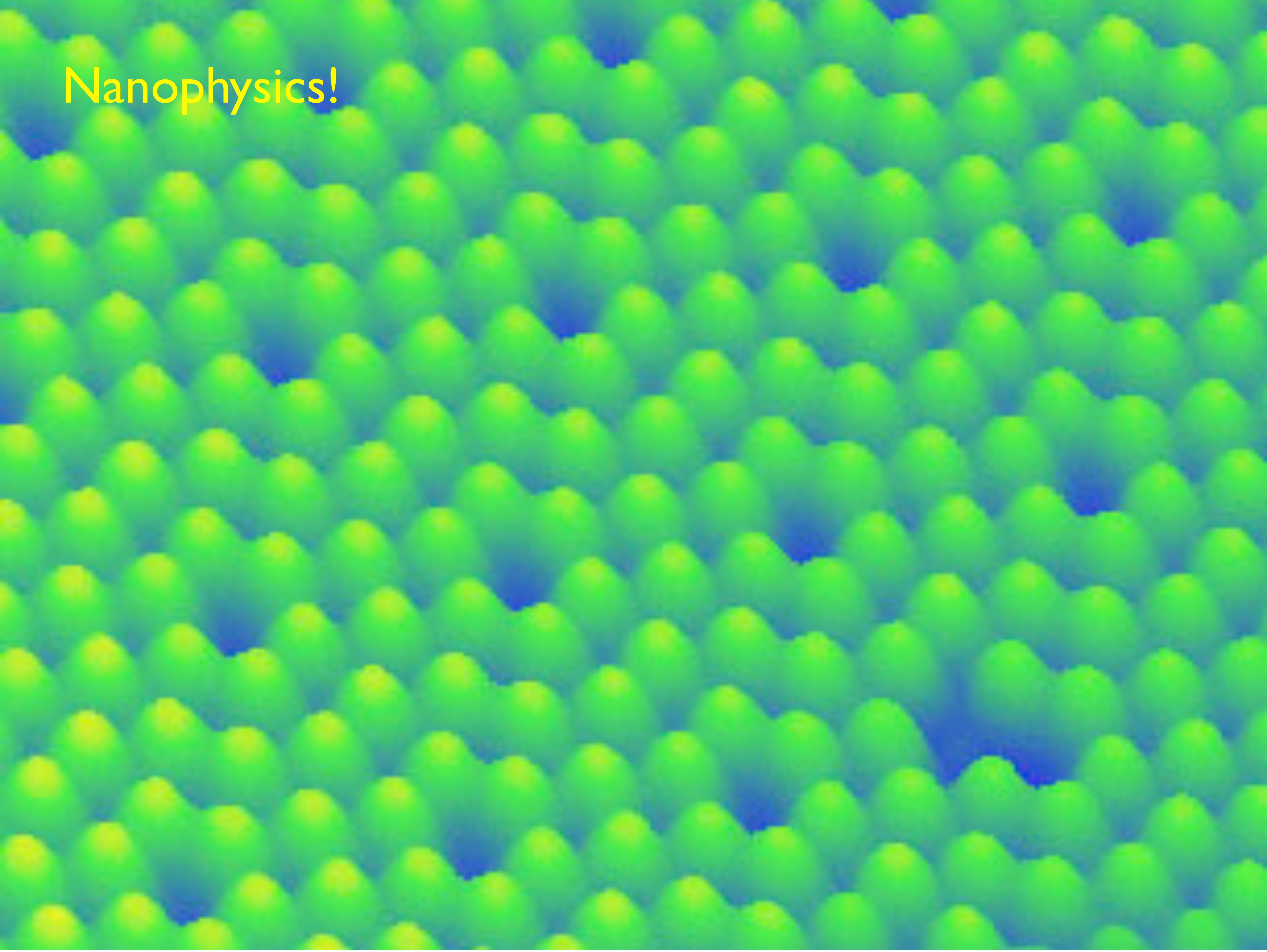
In dieser Arbeit soll gezeigt werden, daß nach der molekularkinetischen Theorie der Wärme in Flüssigkeiten suspendierte Körper von mikroskopisch sichtbarer Größe infolge der Molekularbewegung der Wärme Bewegungen von solcher Größe ausführen müssen, daß diese Bewegungen leicht mit dem Mikroskop nachgewiesen werden können. Es ist möglich, daß die hier zu behandelnden Bewegungen mit der sogenannten „Brownschen Molekularbewegung" identisch sind; die mir erreichbaren Angaben über letztere sind jedoch so ungenau,
[1] daß ich mir hierüber kein Urteil bilden konnte.

Wenn sich die hier zu behandelnde Bewegung samt den für sie zu erwartenden Gesetzmäßigkeiten wirklich beobachten läßt, so ist die klassische Thermodynamik schon für mikroskopisch unterscheidbare Räume nicht mehr als genau gültig anzusehen und es ist dann eine exakte Bestimmung der wahren Atomgröße möglich. Erwiese sich umgekehrt die Voraussage dieser Bewegung als unzutreffend, so wäre damit ein schwerwiegendes Argument gegen die molekularkinetische Auffassung
[2] der Wärme gegeben.

§ 1. Über den suspendierten Teilchen zuzuschreibenden osmotischen Druck.

Im Teilvolumen V^* einer Flüssigkeit vom Gesamtvolumen V seien z-Gramm-Moleküle eines Nichtelektrolyten gelöst. Ist das Volumen V^* durch eine für das Lösungsmittel, nicht aber für die gelöste Substanz durchlässige Wand vom reinen Lösungs-

Nanophysics!



All things are made of atoms–little particles
that move around in perpetual motion,
attracting each other when they are
a little distance apart,
but repelling upon being squeezed
into one another.

—Richard Feynman, *Six Easy Pieces*

Quantum Mechanics

$$-\frac{\hbar^2}{2\mu}\nabla^2\Psi(\mathbf{r}) + [V(\mathbf{r}) - E]\,\Psi(\mathbf{r}) = 0$$

Paul Dirac: "[Schrödinger's equation] accounts for much of physics and all of chemistry"

1991: Schrödinger Professor, University of Vienna

Great Lesson of XXth Century Science

The human scale of space & time is not privileged for understanding Nature . . . and may even be disadvantaged

The world's most powerful microscopes … home to *nanonanophysicists*!

Tevatron collider at Fermilab

protons on antiprotons at 1+1 TeV

speed of light: $c \approx 10^9$ km/h

speed of protons: c – 495 km/h

Large Hadron Collider at CERN

protons on protons at 3.5+3.5 TeV

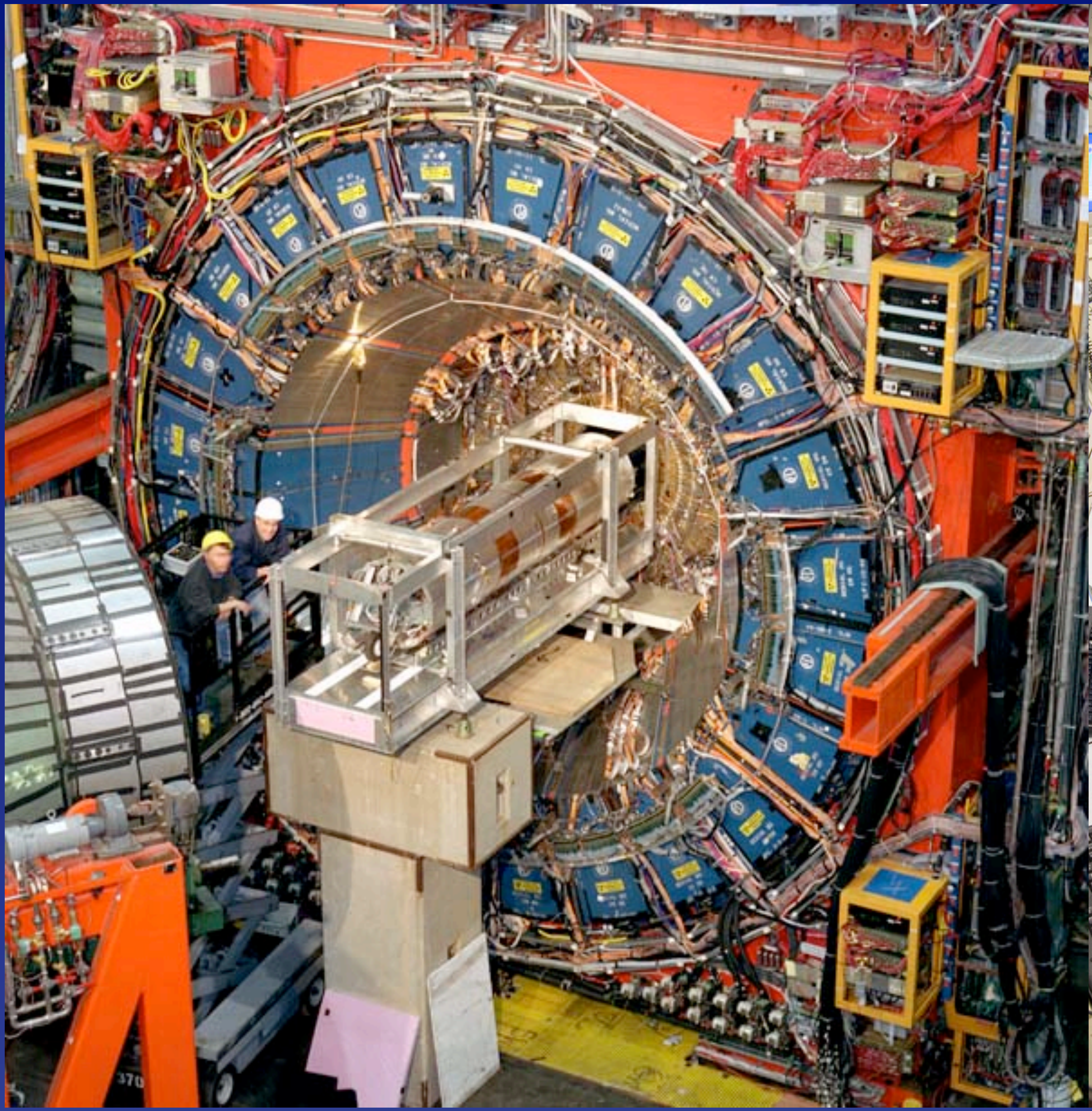
speed of protons: c – 39 km/h

soon: c – 10 km/h

→ 100 million collisions per second

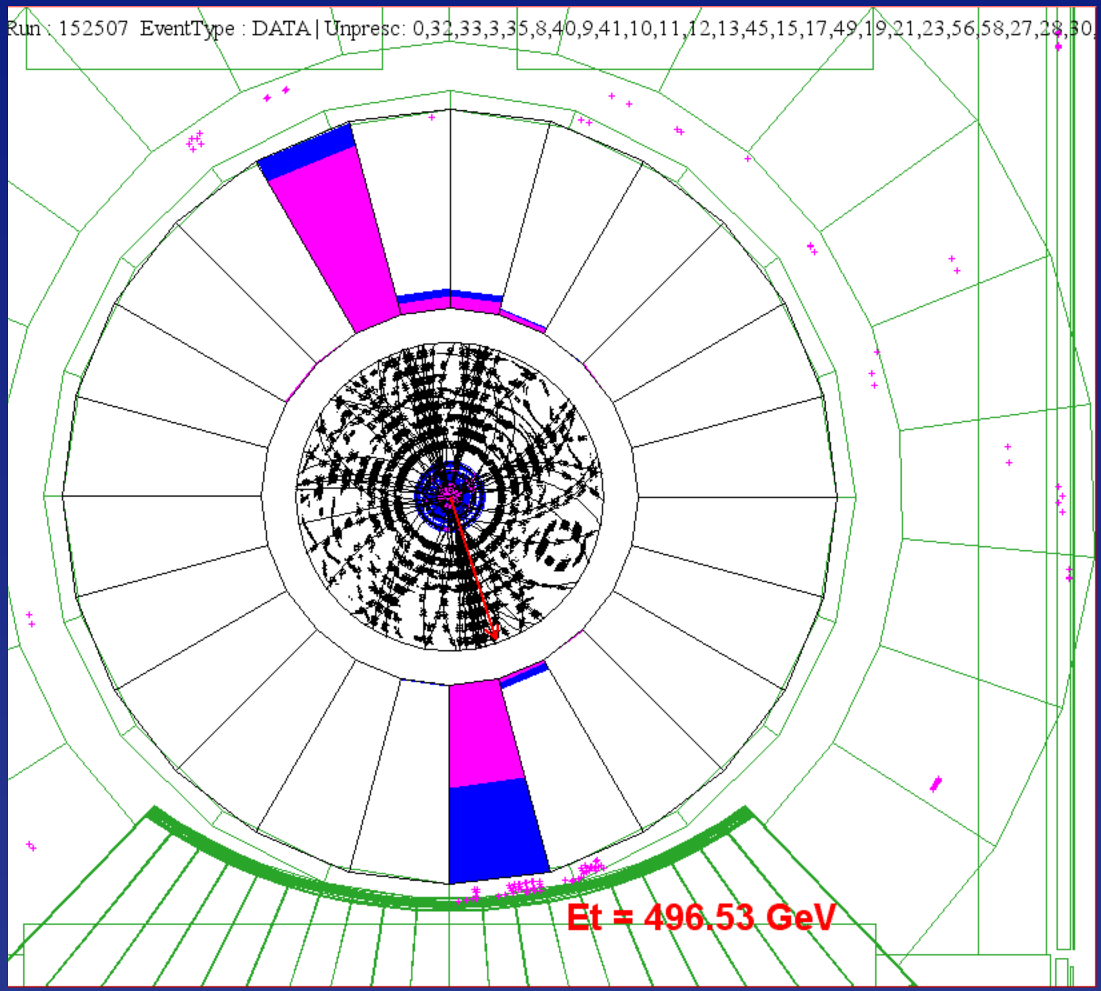

CDF
CQ
D0
www.fnal.gov

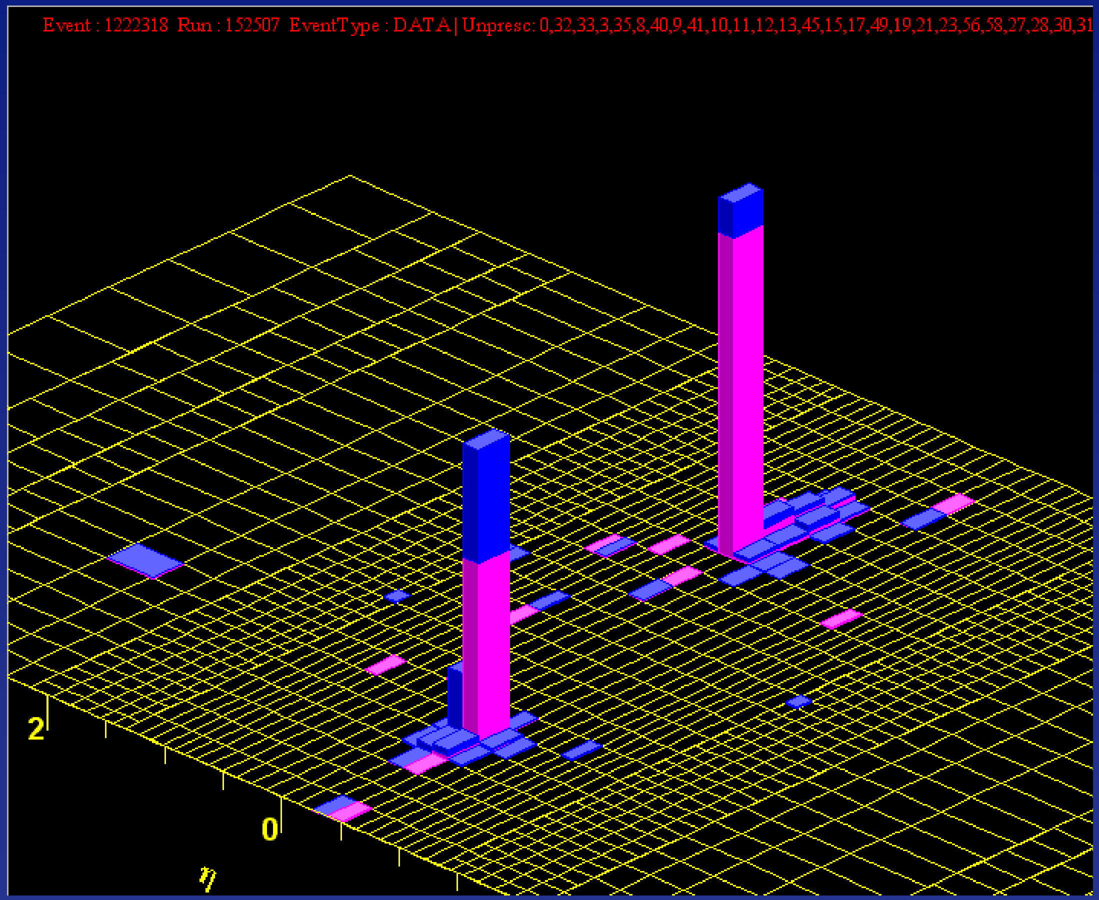
CDF Experiment



The World's Most Powerful Microscopes

nanonanophysics



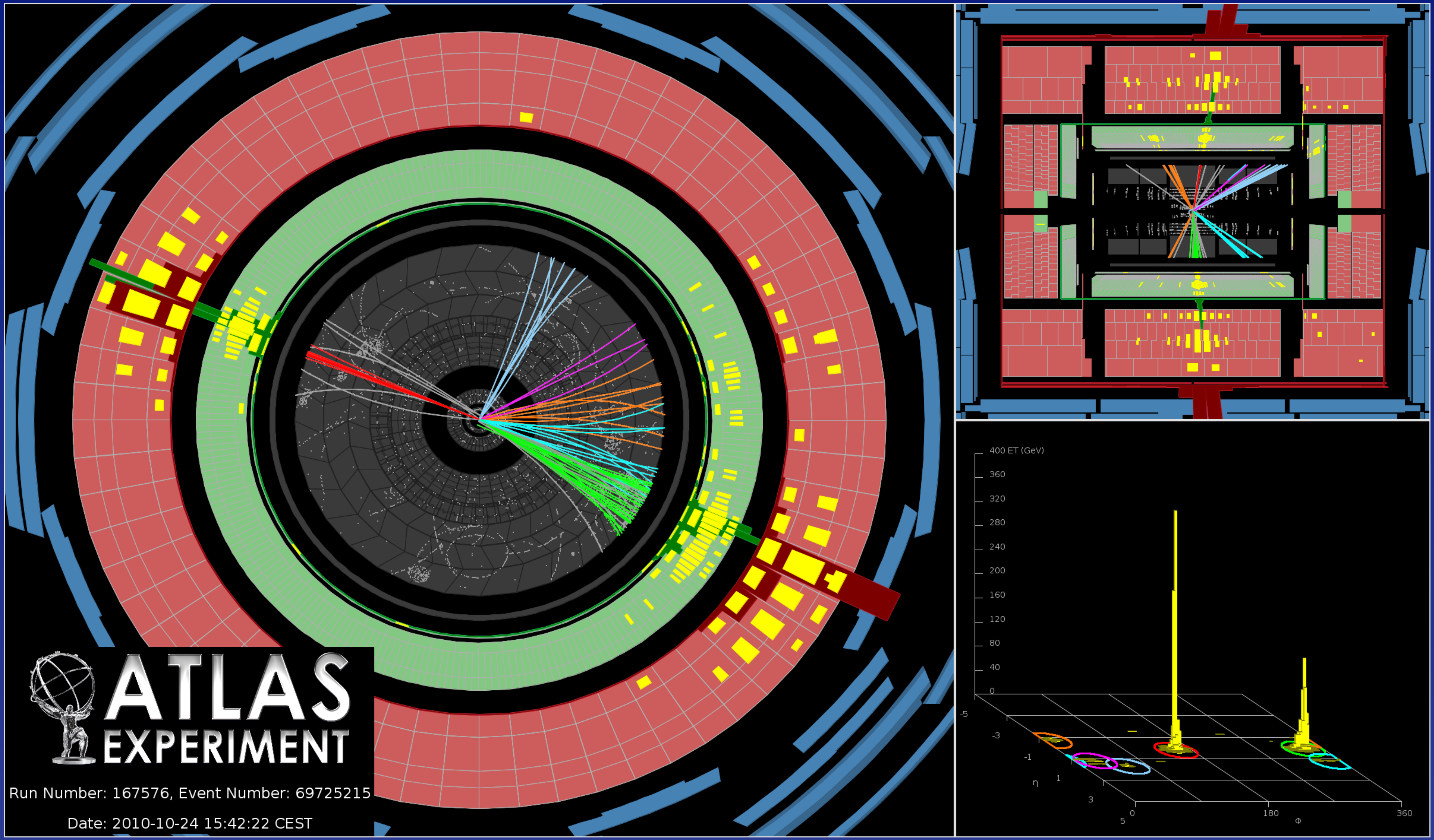


CDF two-jet event (70% of energy ⊥ beam direction)

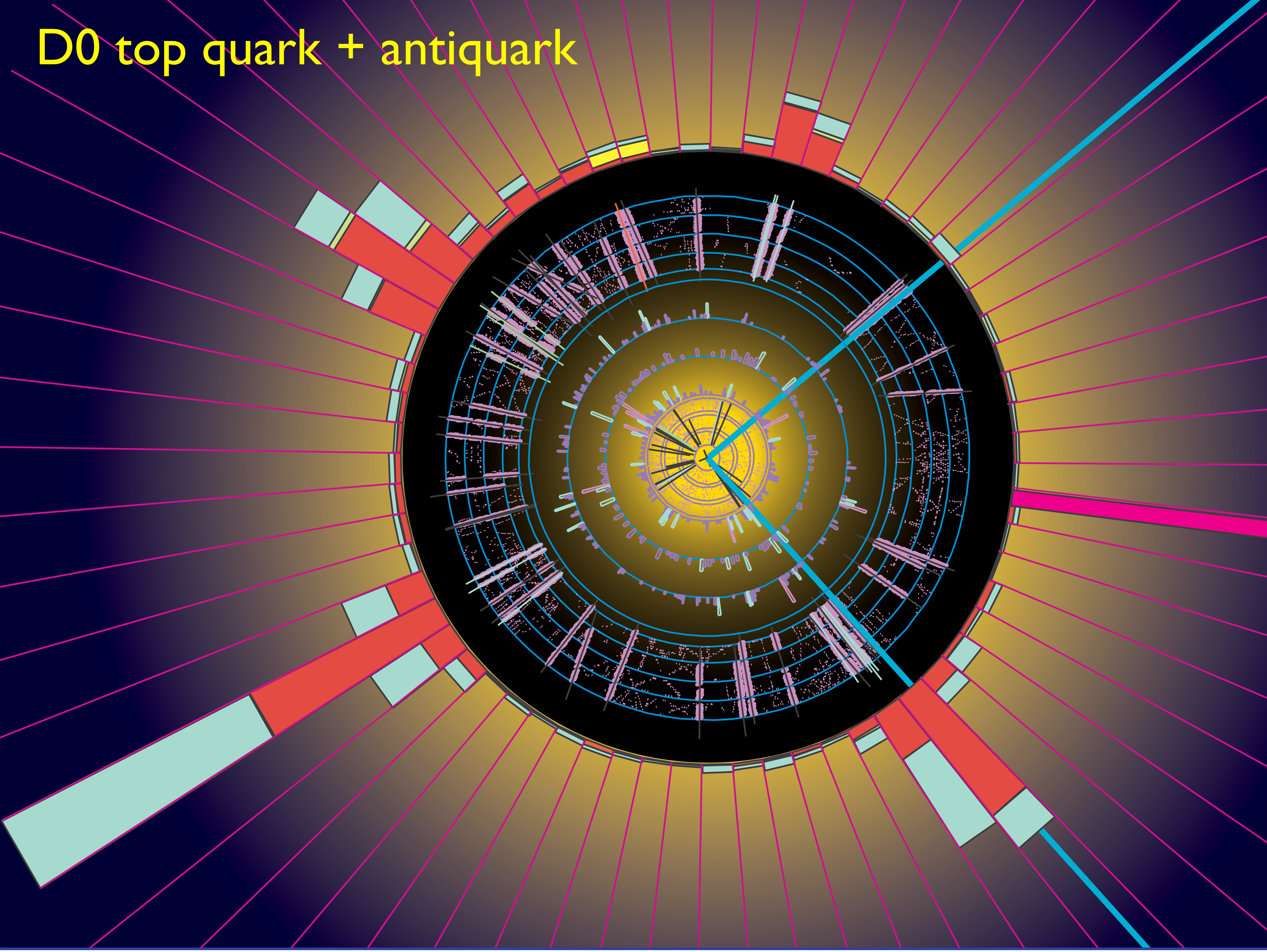
quark + antiquark → jet + jet

The World's Most Powerful Microscopes

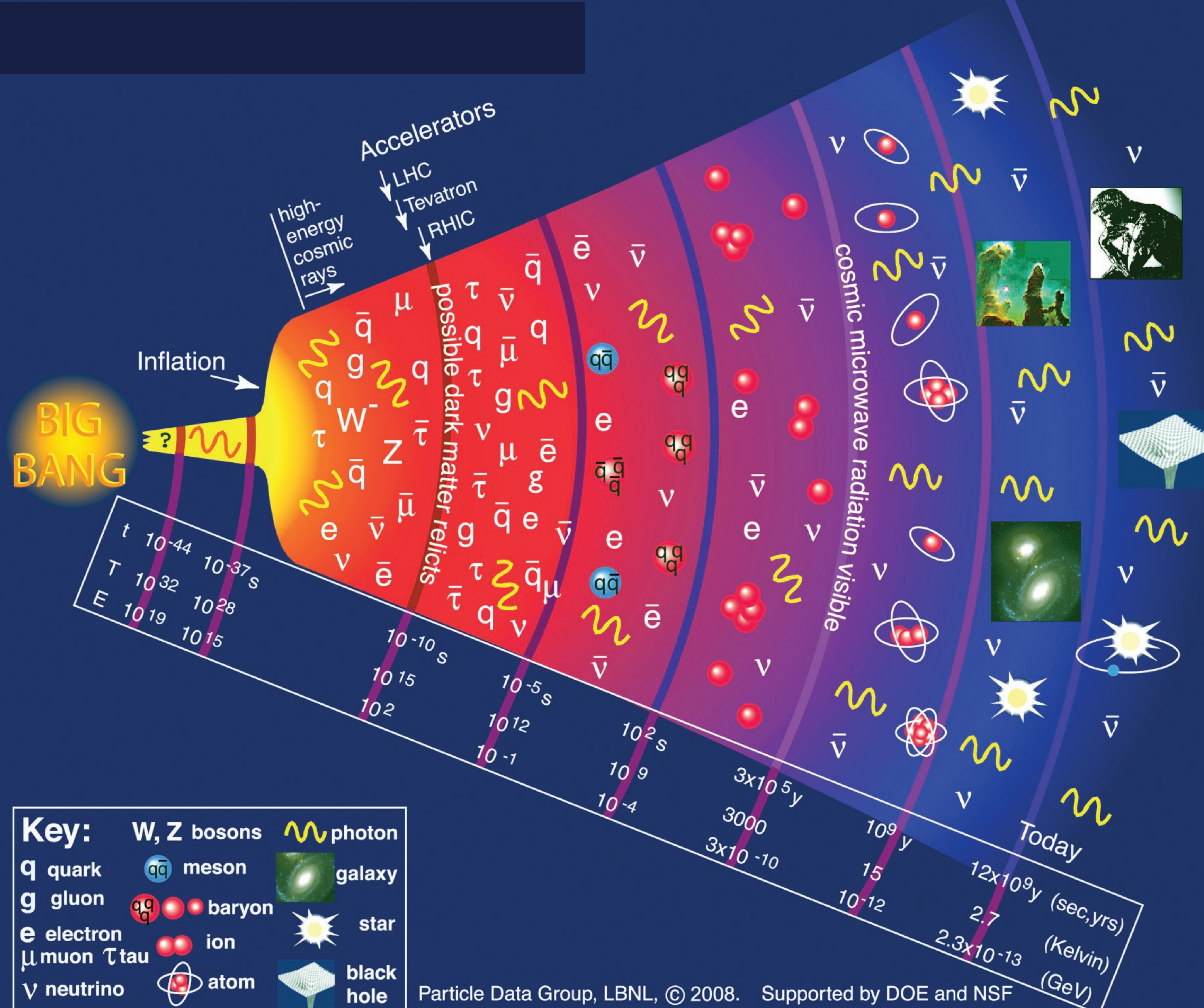
nanonanophysics



Transverse momenta: 1.3 TeV + 1.2 TeV

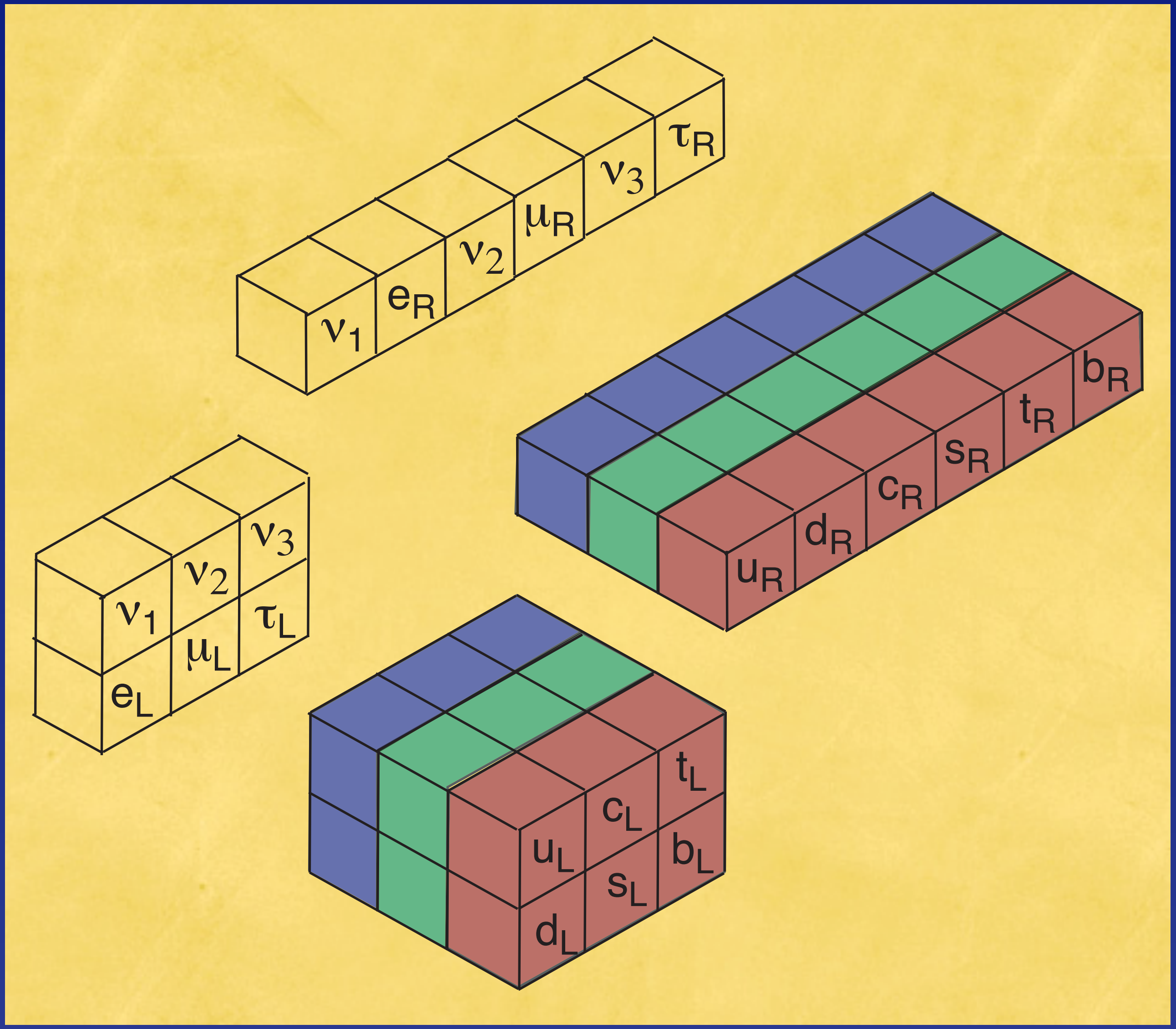

D0 top quark + antiquark

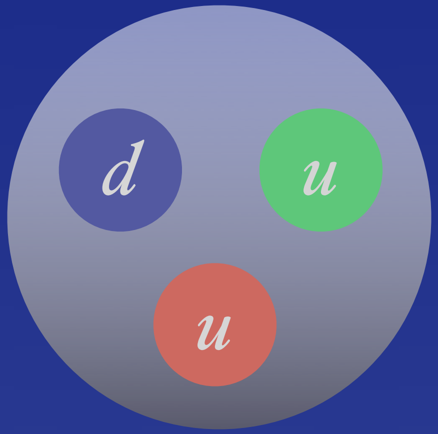
Accelerators as time machines …



Our Picture of Matter (the revolution just past)

Pointlike ($r \leq 10^{-18}$ m) quarks and leptons



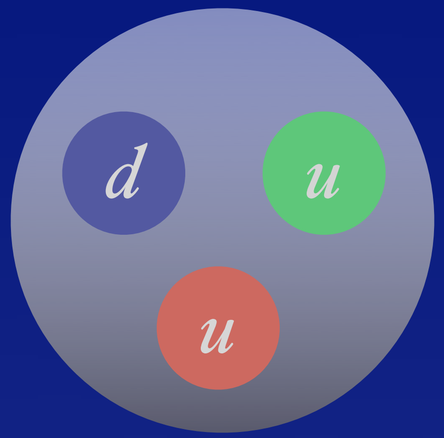


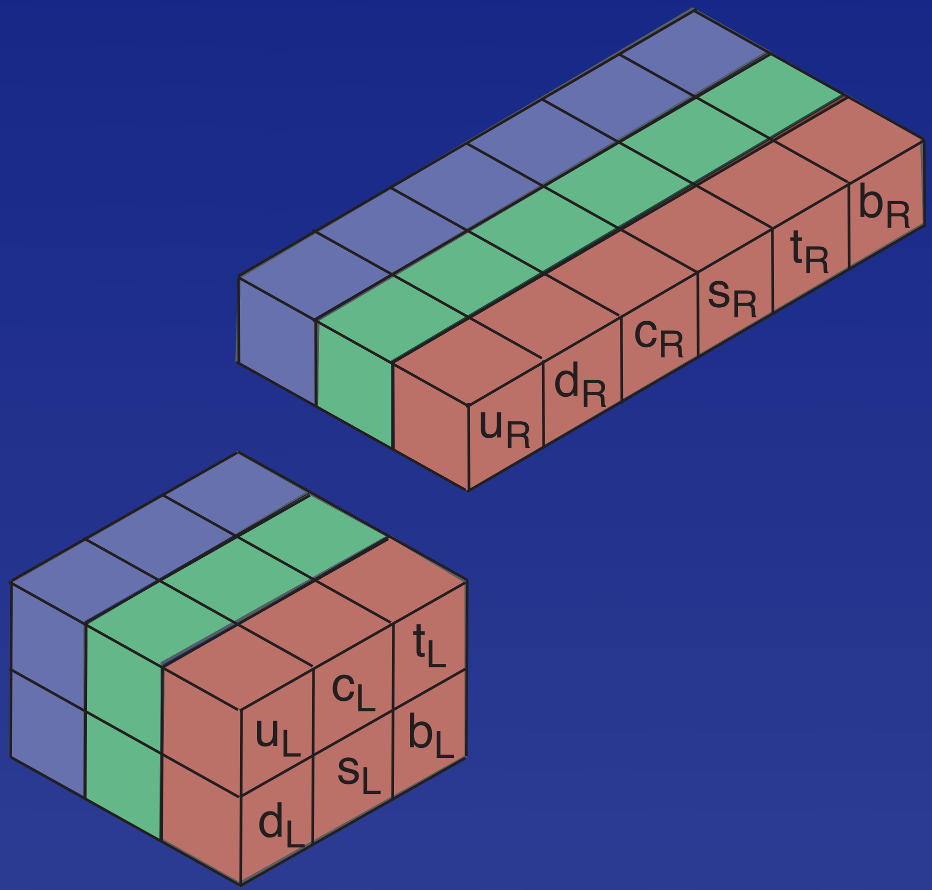
Gravitation, electromagnetism, radioactivity, strong interaction

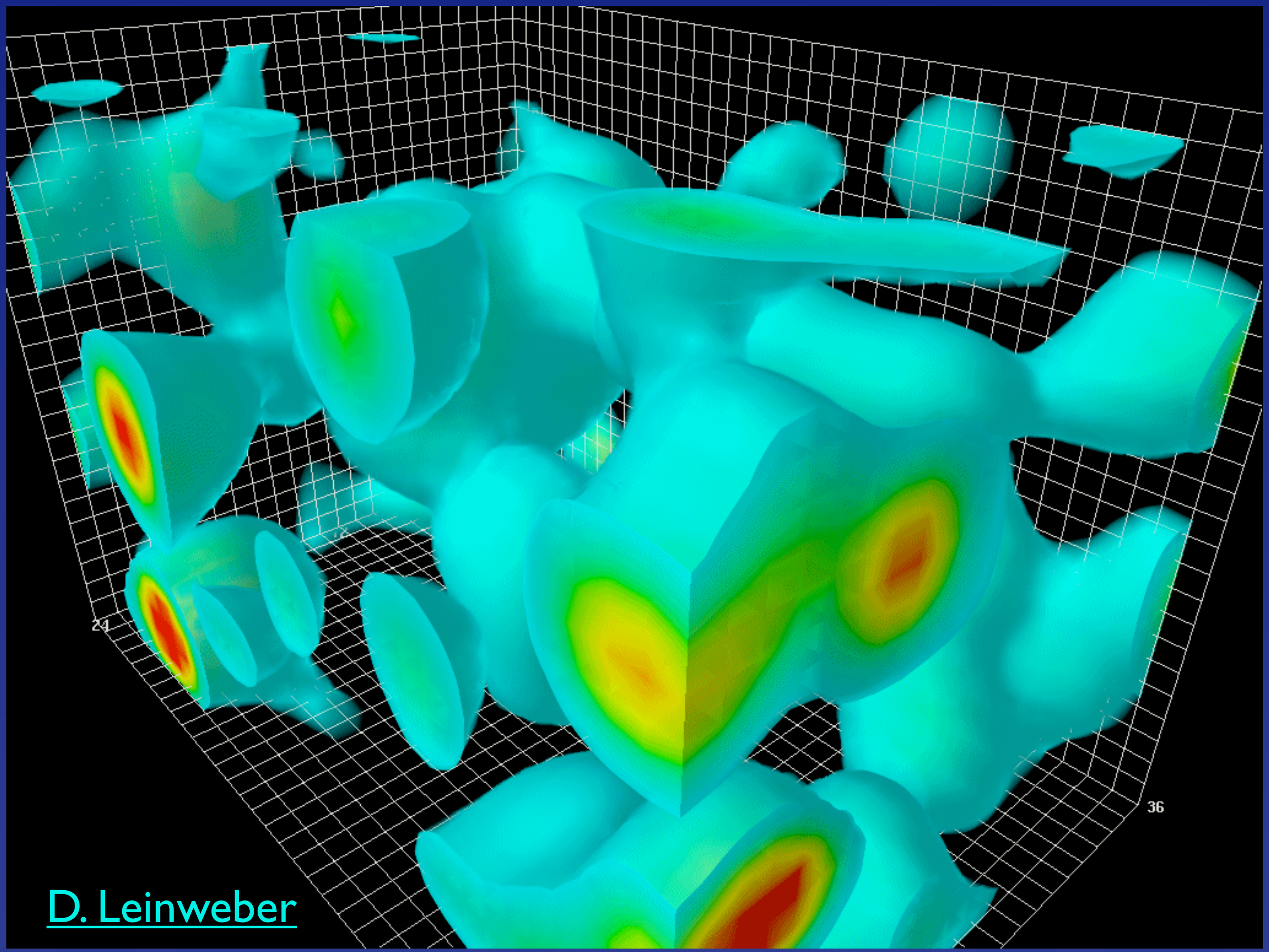
New Law of Nature #1

Quantum chromodynamics (QCD):
color symmetry among quarks
red · green · blue

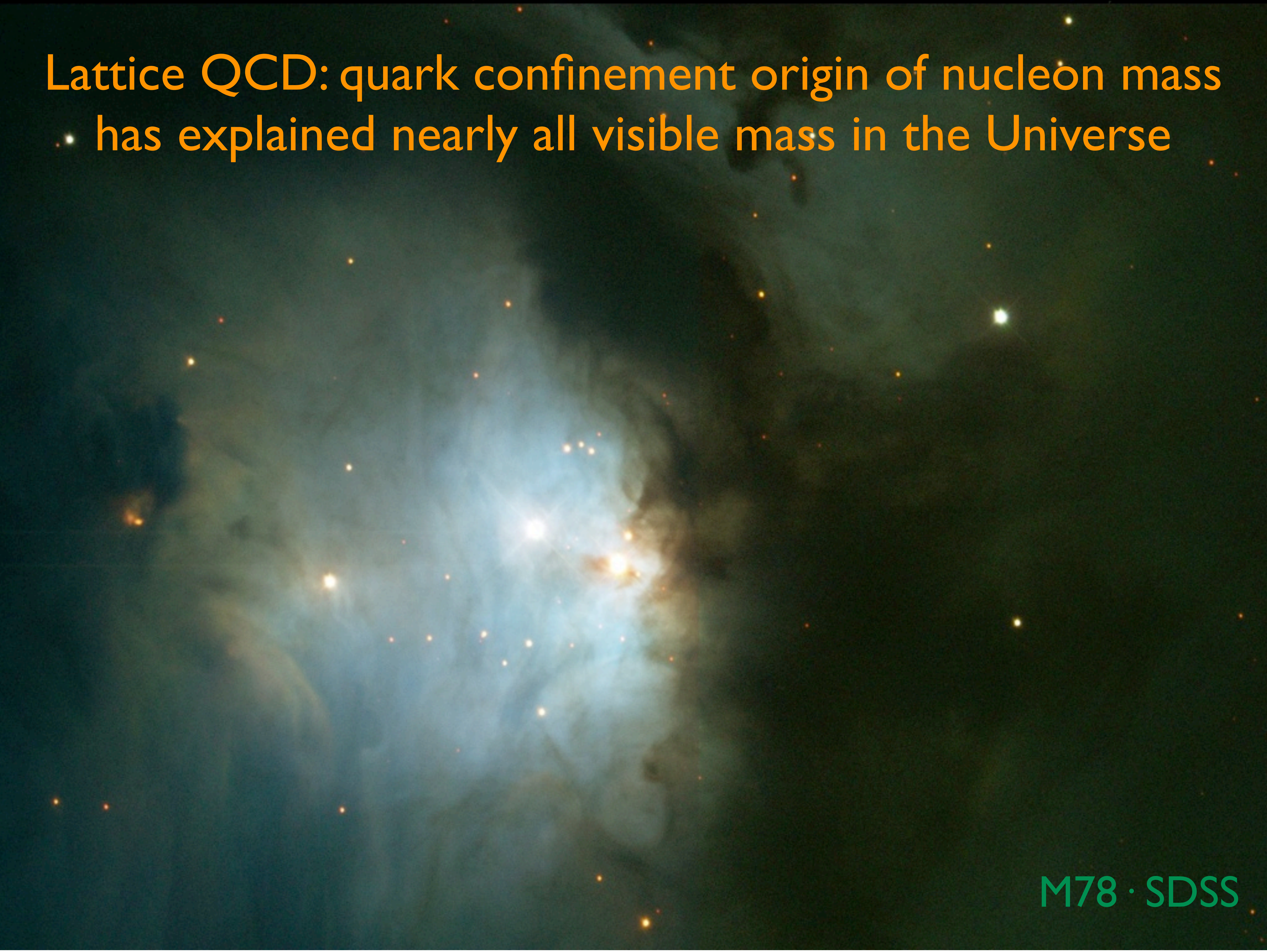
gluons







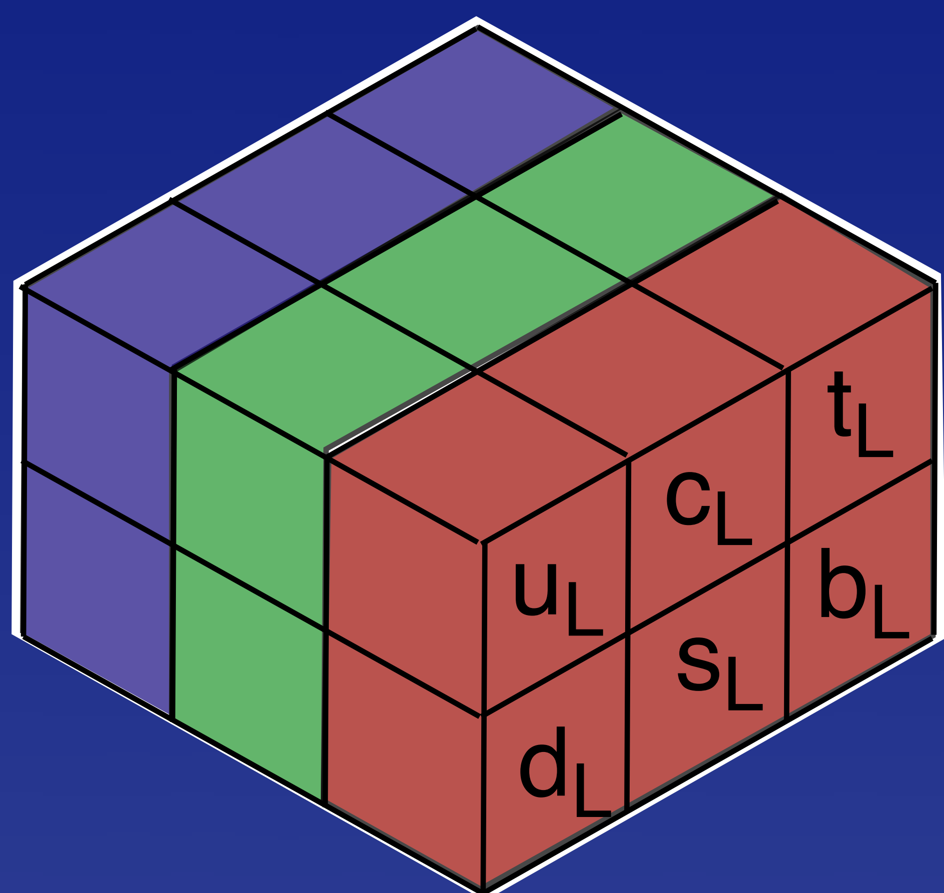
Lattice QCD: quark confinement origin of nucleon mass has explained nearly all visible mass in the Universe

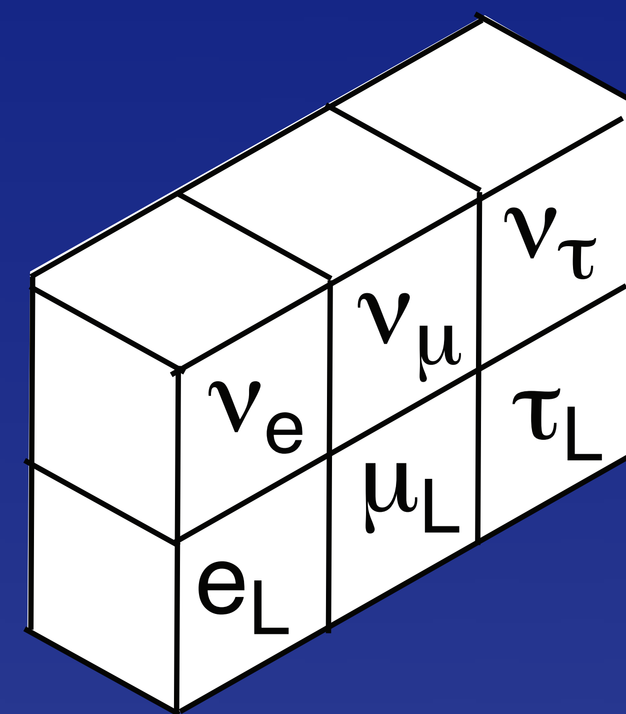


New Law of Nature #2

Electroweak theory:
family symmetry
u ↔ d ; ν ↔ e ; …

weak bosons (W^+, W^-, Z^0) + photon



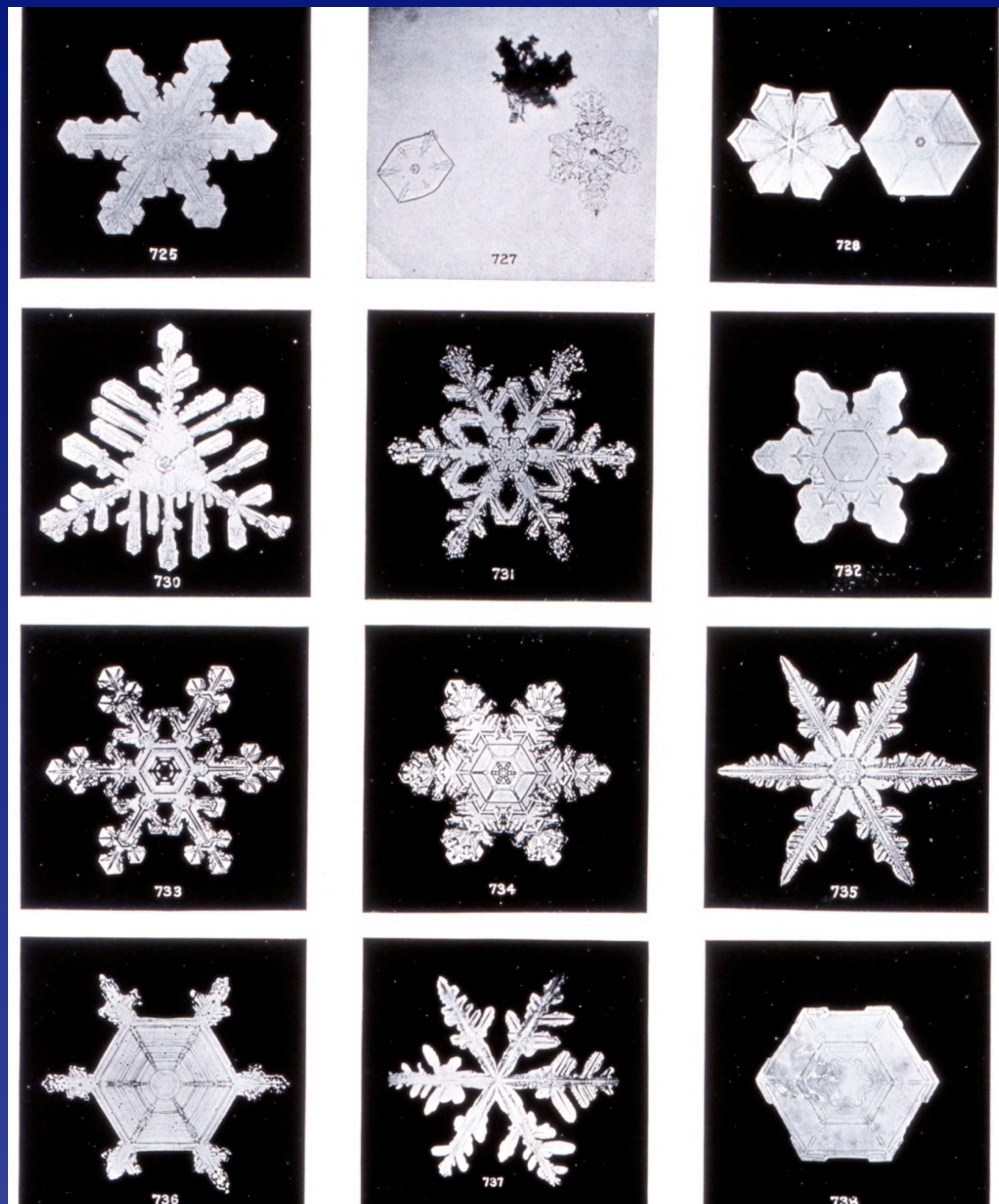


Weak interactions, electromagnetism seem so different …

Weak	Electromagnetic
range: 1% proton size	infinite range
W: 90 × proton mass	massless photon

How can they share a common origin (symmetry)?

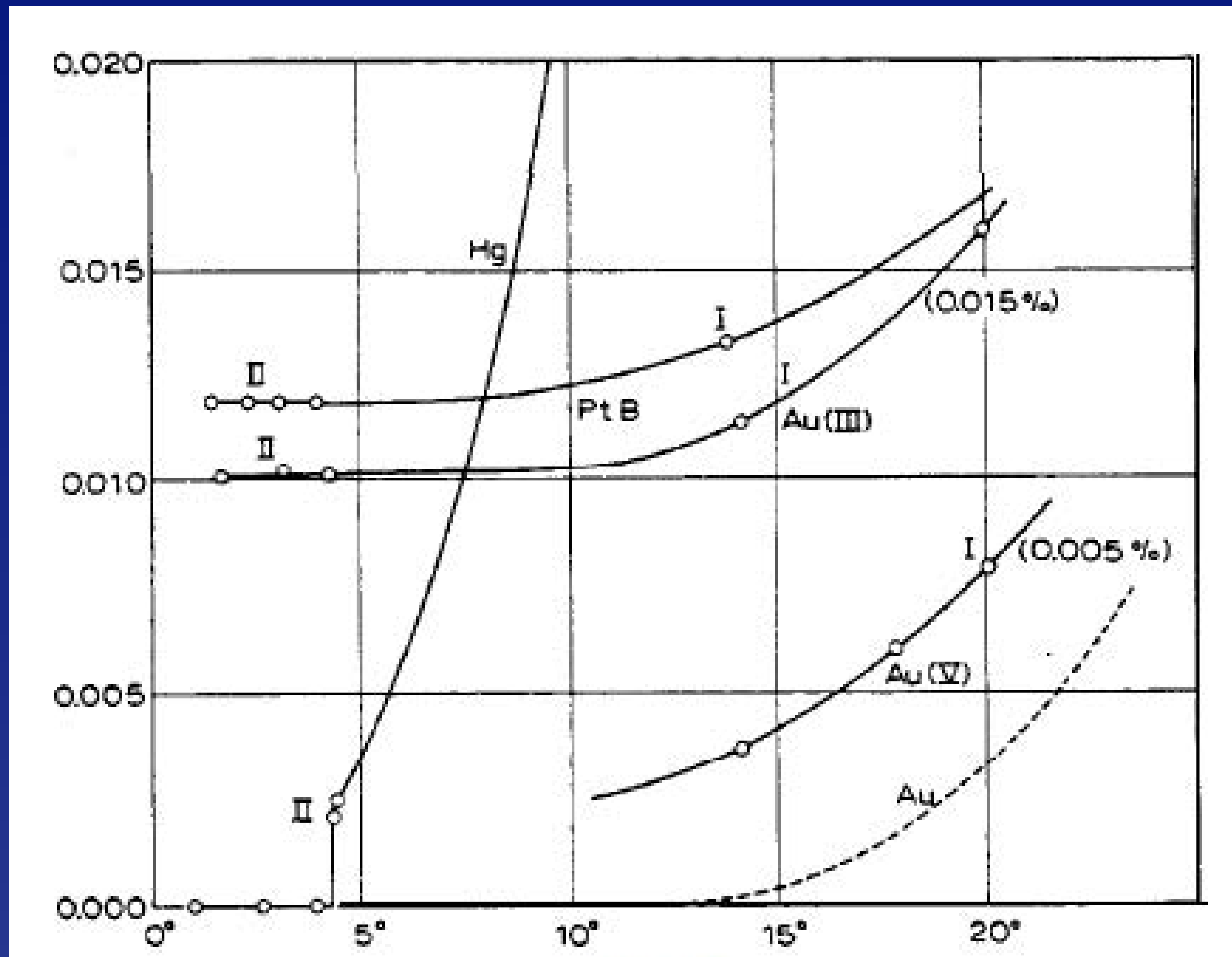
Symmetry of laws $\not\Rightarrow$ symmetry of outcomes



Studies among the Snow Crystals ... by Wilson Bentley, via NOAA Photo Library

Heike Kamerlingh Onnes, 1911: *Superconductivity*

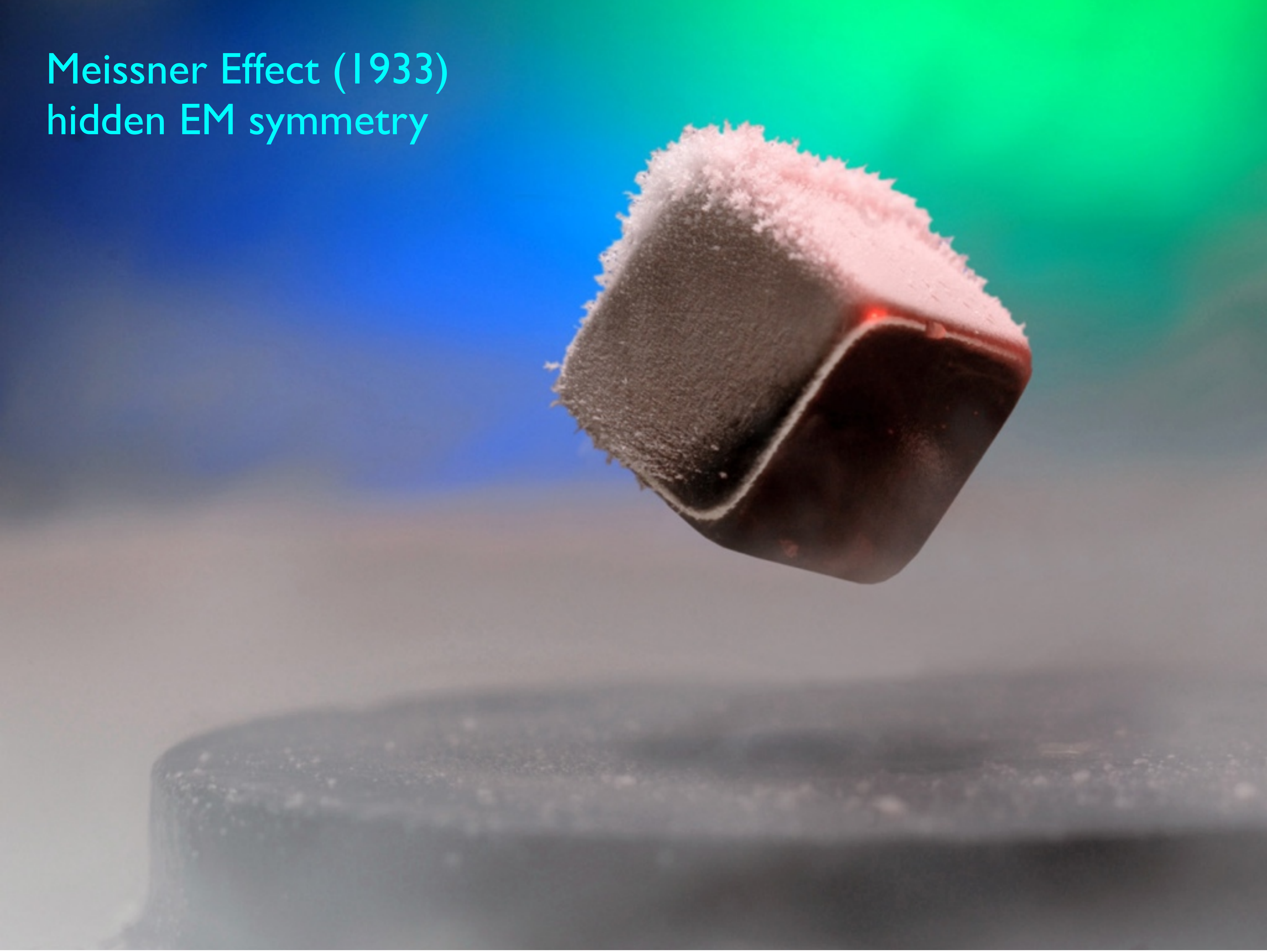
Resistance relative to 0° C



Temperature [K]

Mercury loses all resistance at 4.2 K

Meissner Effect (1933)
hidden EM symmetry



Meissner effect suggests that
a field that permeates all of space
could hide electroweak symmetry

Peter Higgs

+ R. Brout†, F. Englert, G. Guralnik, R. Hagen, T. Kibble

“Standard” Electroweak Theory

Higgs boson: massive particle with spin zero

hides electroweak symmetry

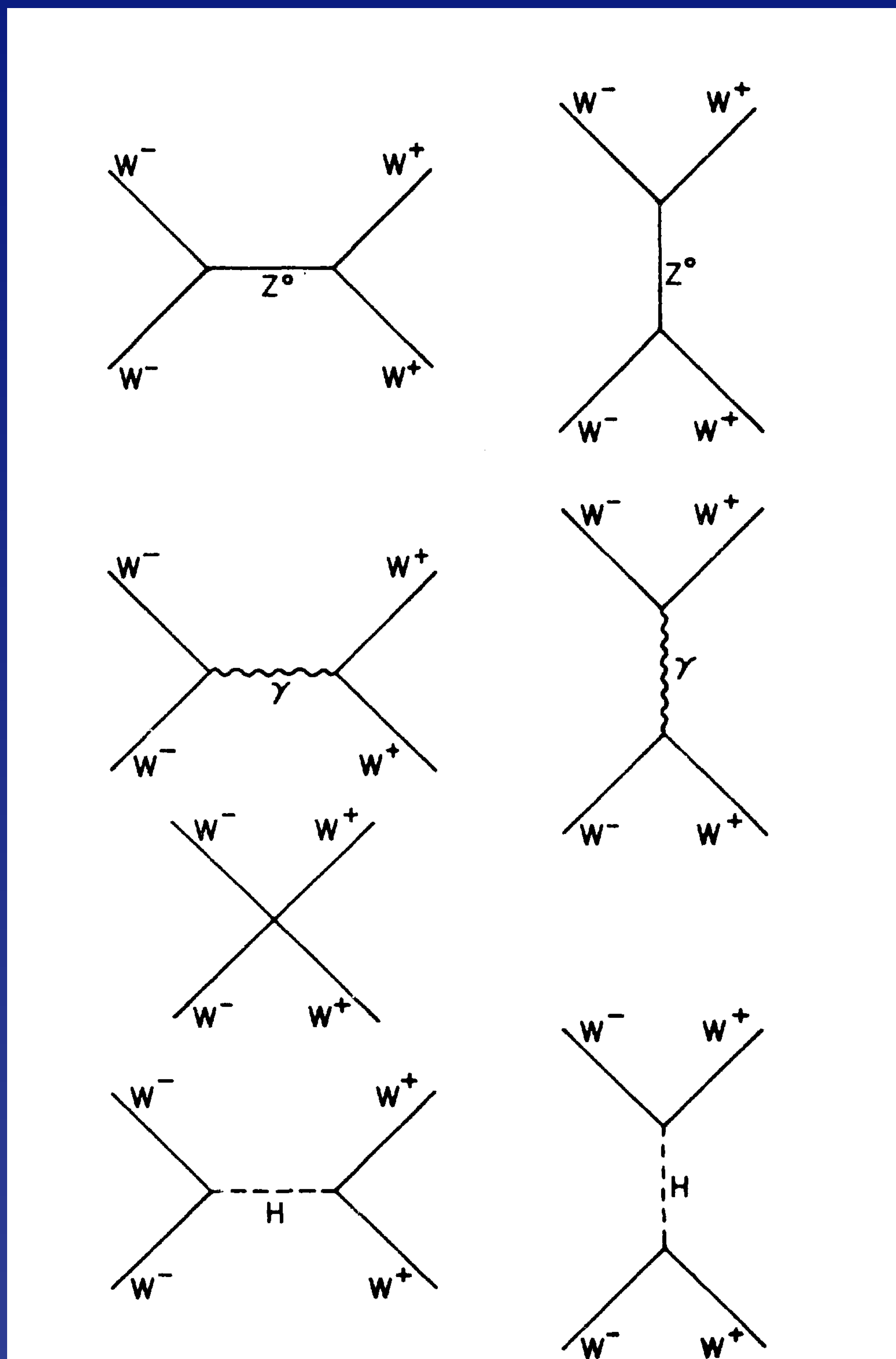
gives mass to W and Z

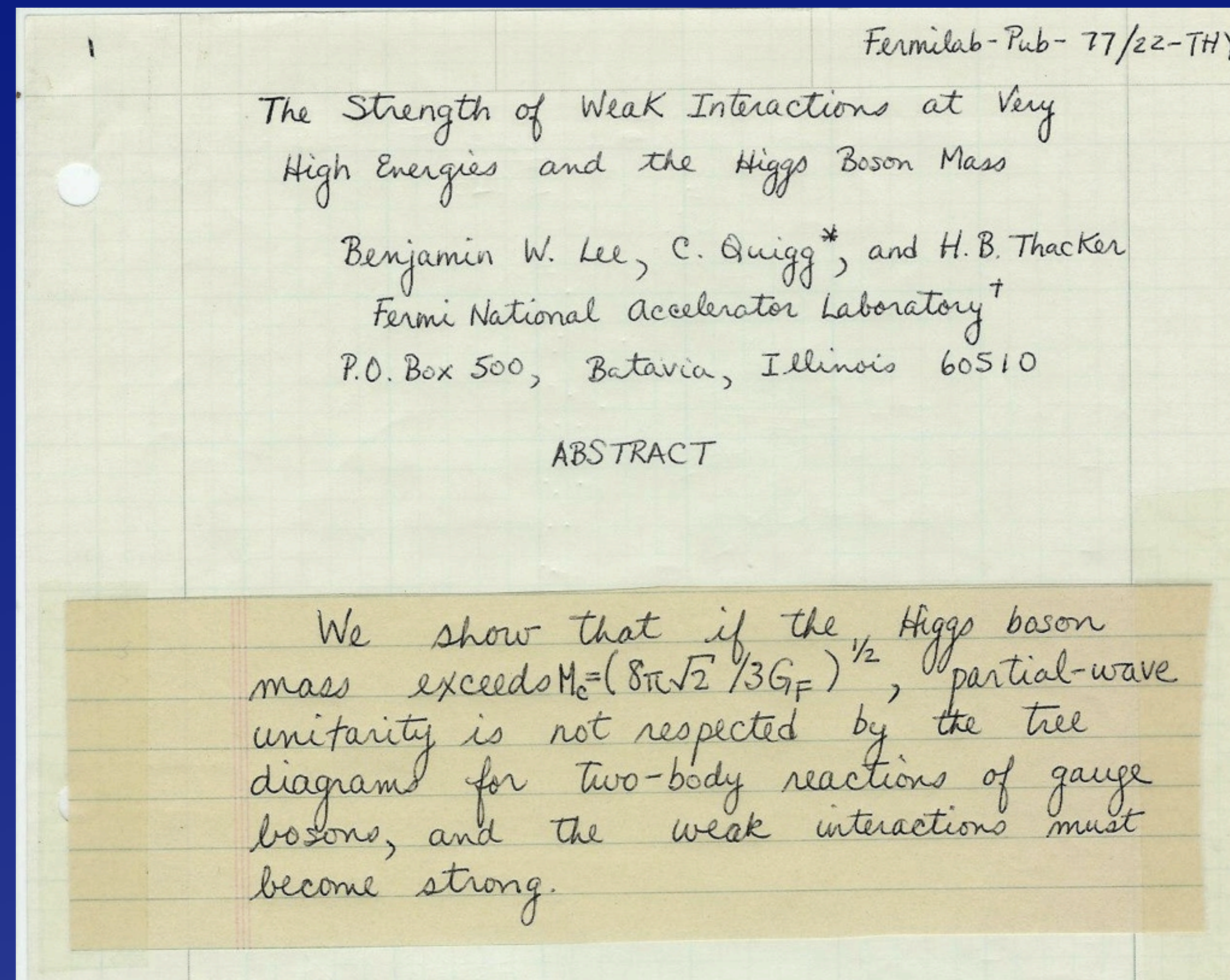
gives mass to electron, quarks, etc.

Theory does not predict Higgs-boson mass

Not yet observed!

Gedankenexperiment





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Fermilab-Pub-77/22-THY

The Strength of Weak Interactions at Very High Energies and the Higgs Boson Mass

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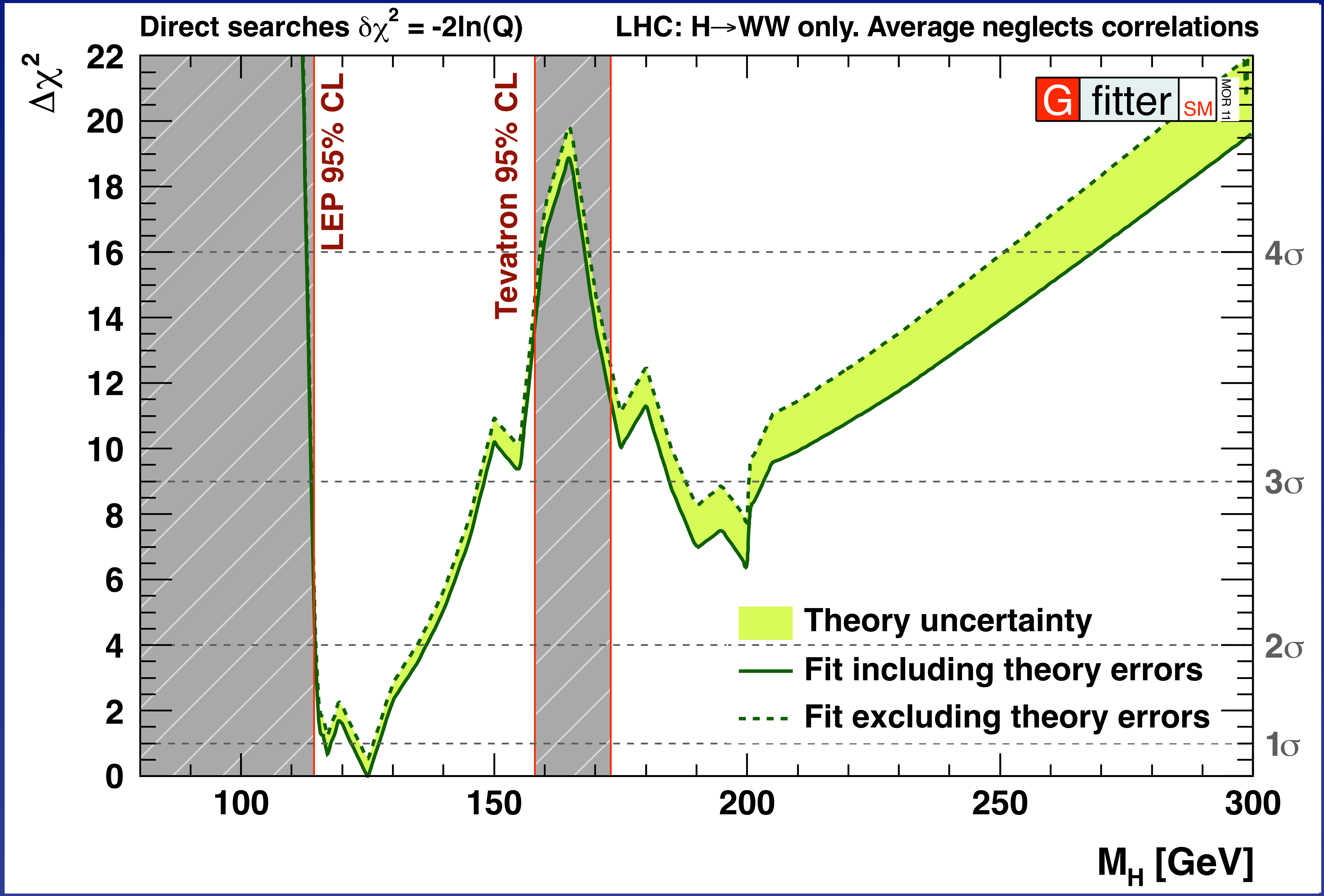
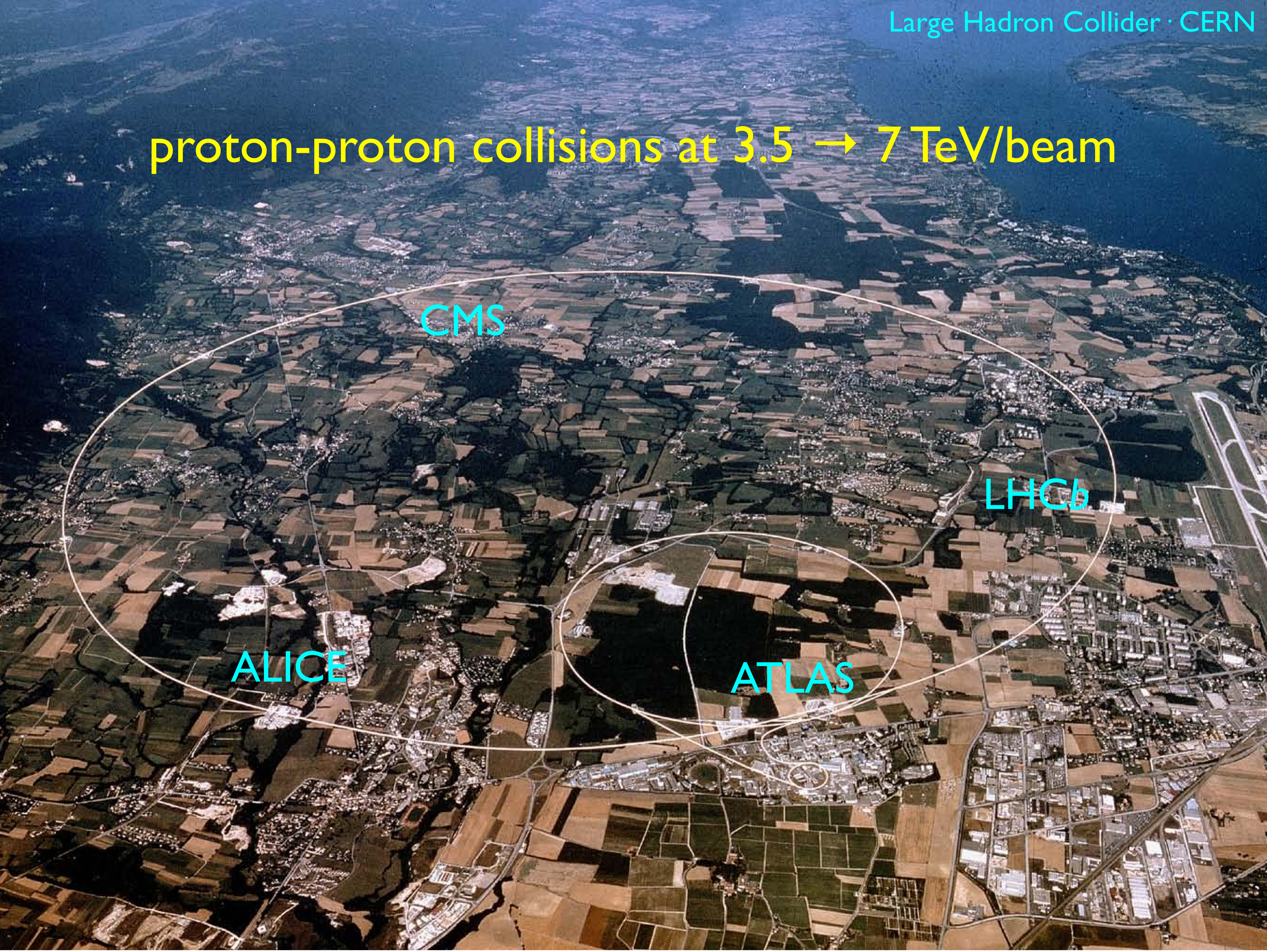
ABSTRACT

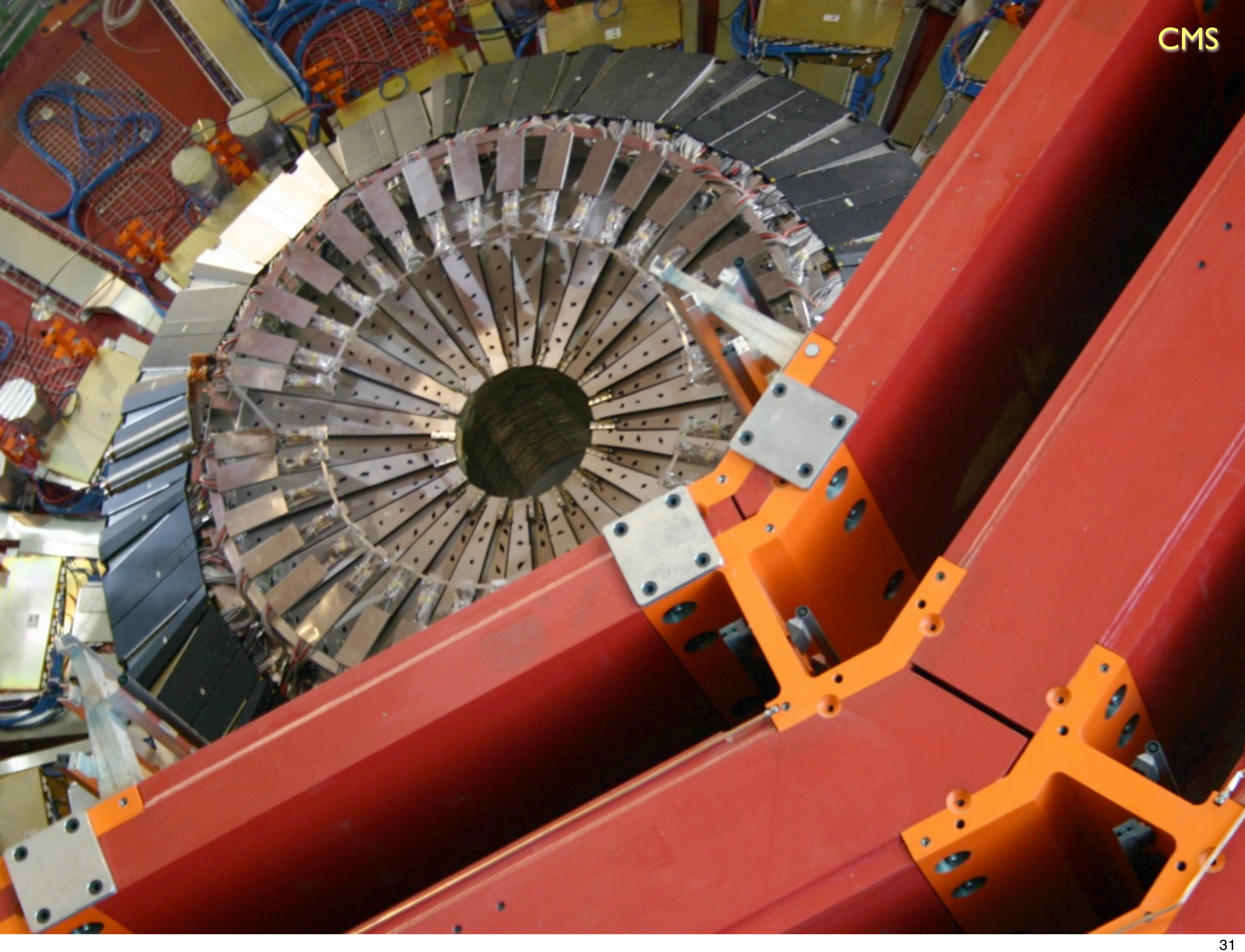
We show that if the Higgs boson mass exceeds $M_c = (8\pi\sqrt{2}/3G_F)^{1/2}$, partial-wave unitarity is not respected by the tree diagrams for two-body reactions of gauge bosons, and the weak interactions must become strong.

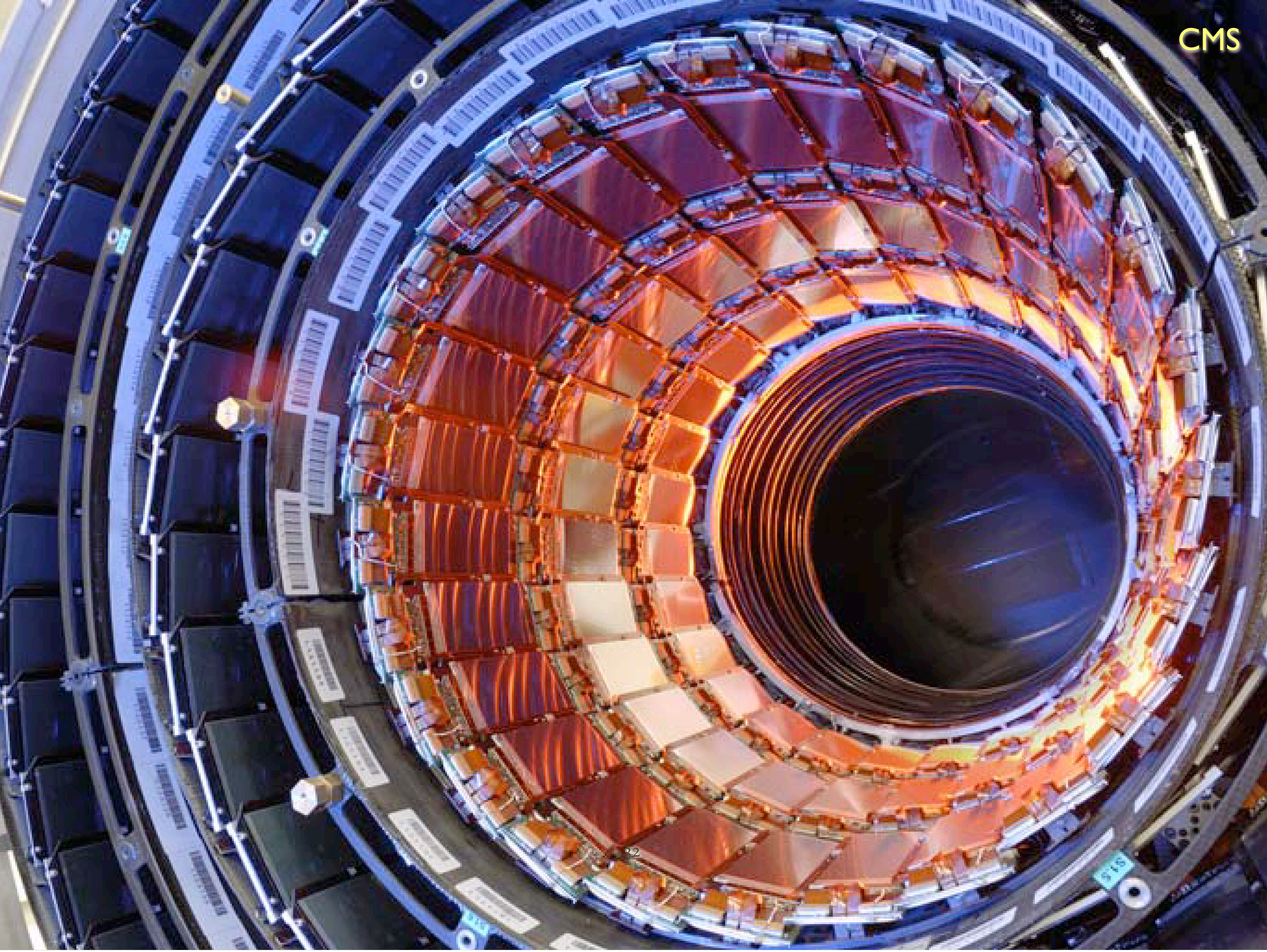
TeV energy scale!

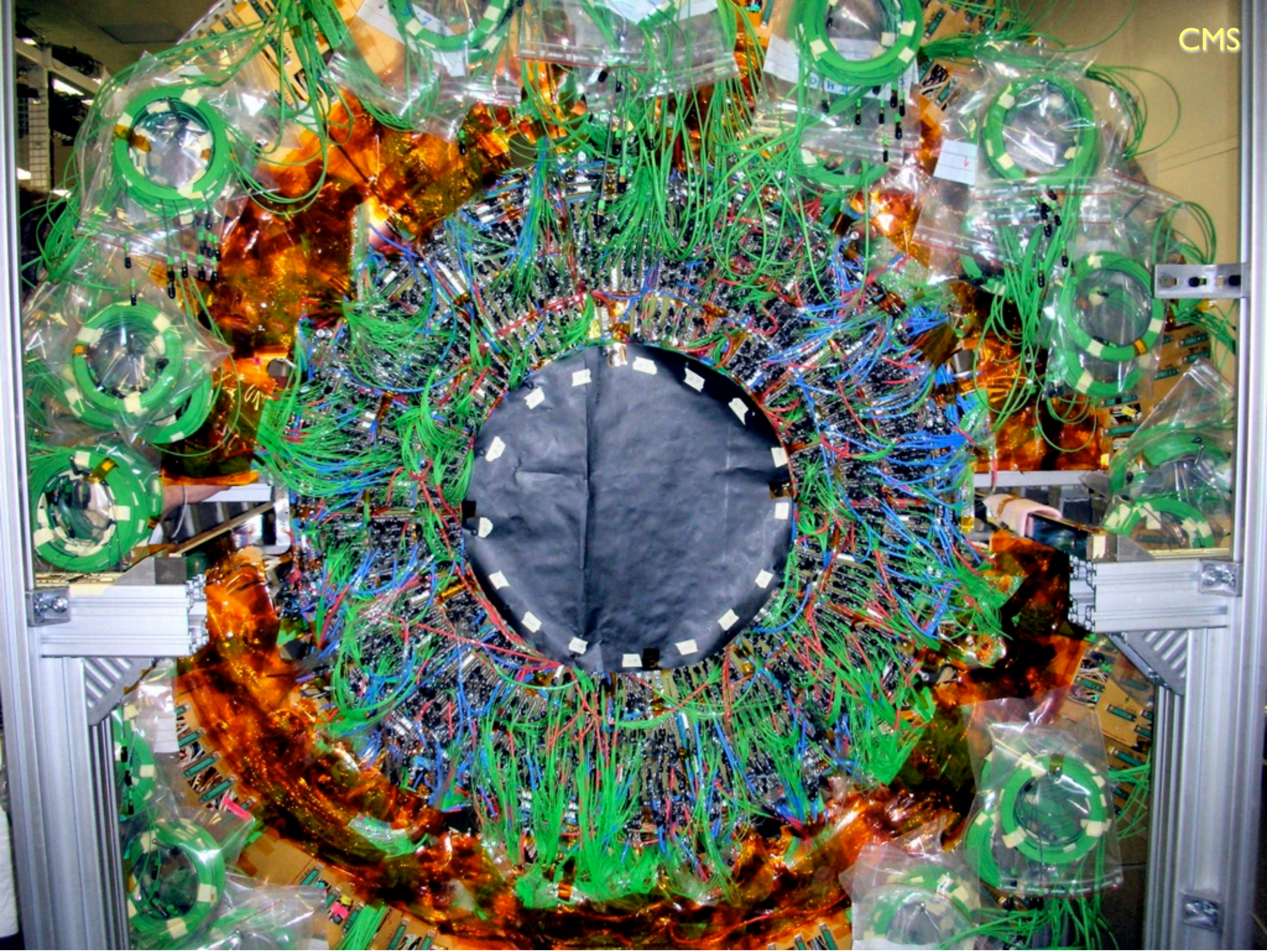
Where the (standard) Higgs boson might be

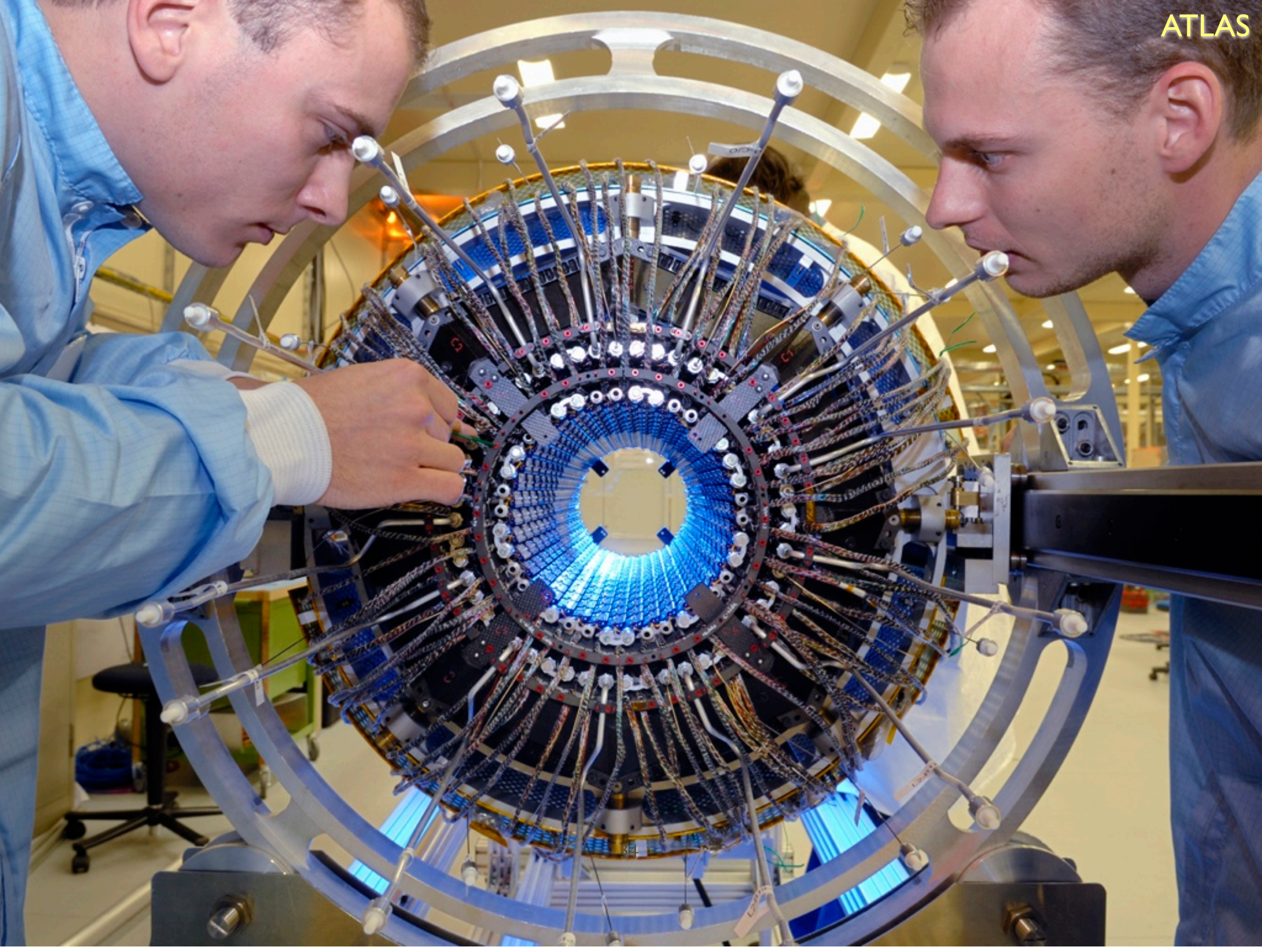


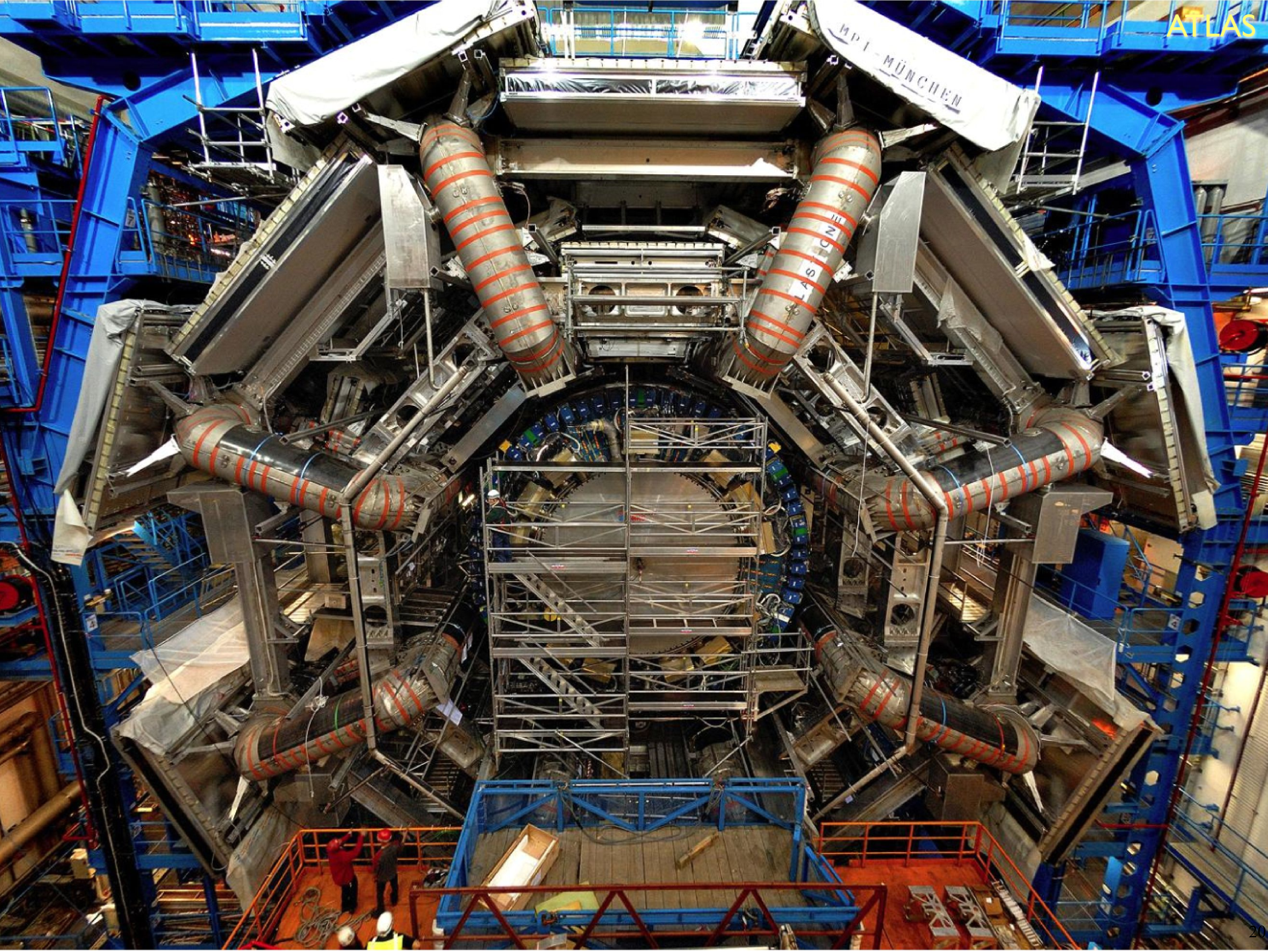

Large Hadron Collider · CERN
proton-proton collisions at 3.5 → 7 TeV/beam
CMS
LHC*b*
ALICE
ATLAS


CMS


CMS


CMS


ATLAS


ATLAS
MPI-MÜNCHEN

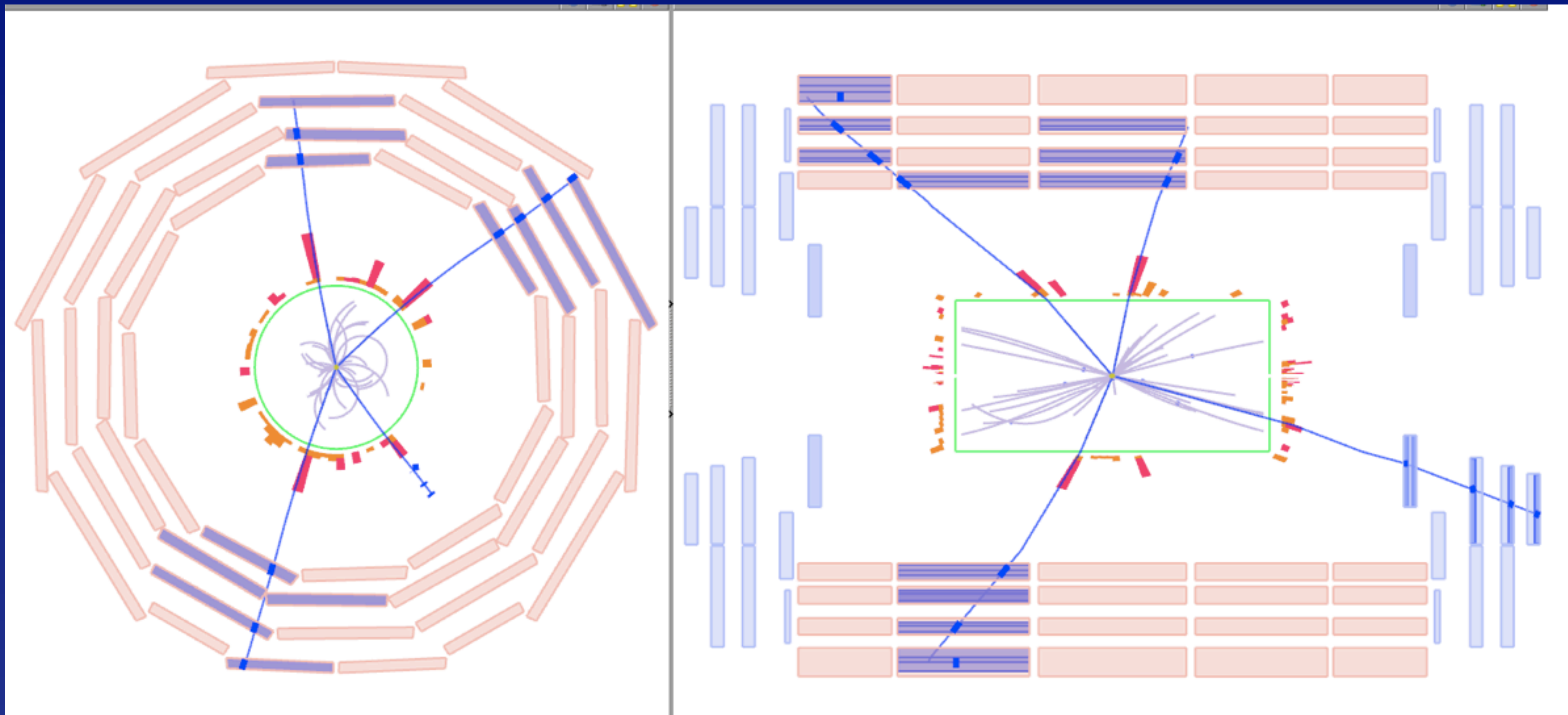
Fabiola Gianotti (ATLAS) : *If we do not find the Higgs boson, that means that the theory is just wrong!*

What hides the electroweak symmetry?

- New kind of force? (Higgs boson)
- New force from a new symmetry?
- Residual force from strong dynamics?
- Echo of extra spacetime dimensions?

Which path has nature taken?

How a heavy Higgs boson would appear



CMS event: 7-TeV pp

Invariant Masses

$\mu_0 + \mu_1$: 92.15 GeV (total(Z) p_T 26.5 GeV, ϕ -3.03),
$\mu_2 + \mu_3$: 92.24 GeV (total(Z) p_T 29.4 GeV, ϕ +.06),
$\mu_0 + \mu_2$: 70.12 GeV (total p_T 27 GeV),
$\mu_3 + \mu_1$: 83.1 GeV (total p_T 26.1 GeV).

Invariant Mass of 4μ: 201 GeV

Why will it matter?

Understanding the everyday …

Why atoms?

Why chemistry?

Why stable structures?

Without a Higgs mechanism …

Electron and quarks would have no mass

QCD would confine quarks into protons, etc.

Proton mass little changed

Surprise: QCD would hide EW symmetry,

give tiny masses to W, Z

Massless electron: atoms lose integrity

No atoms means no chemistry, no stable composite structures like liquids, solids, …

… *character of the physical world*

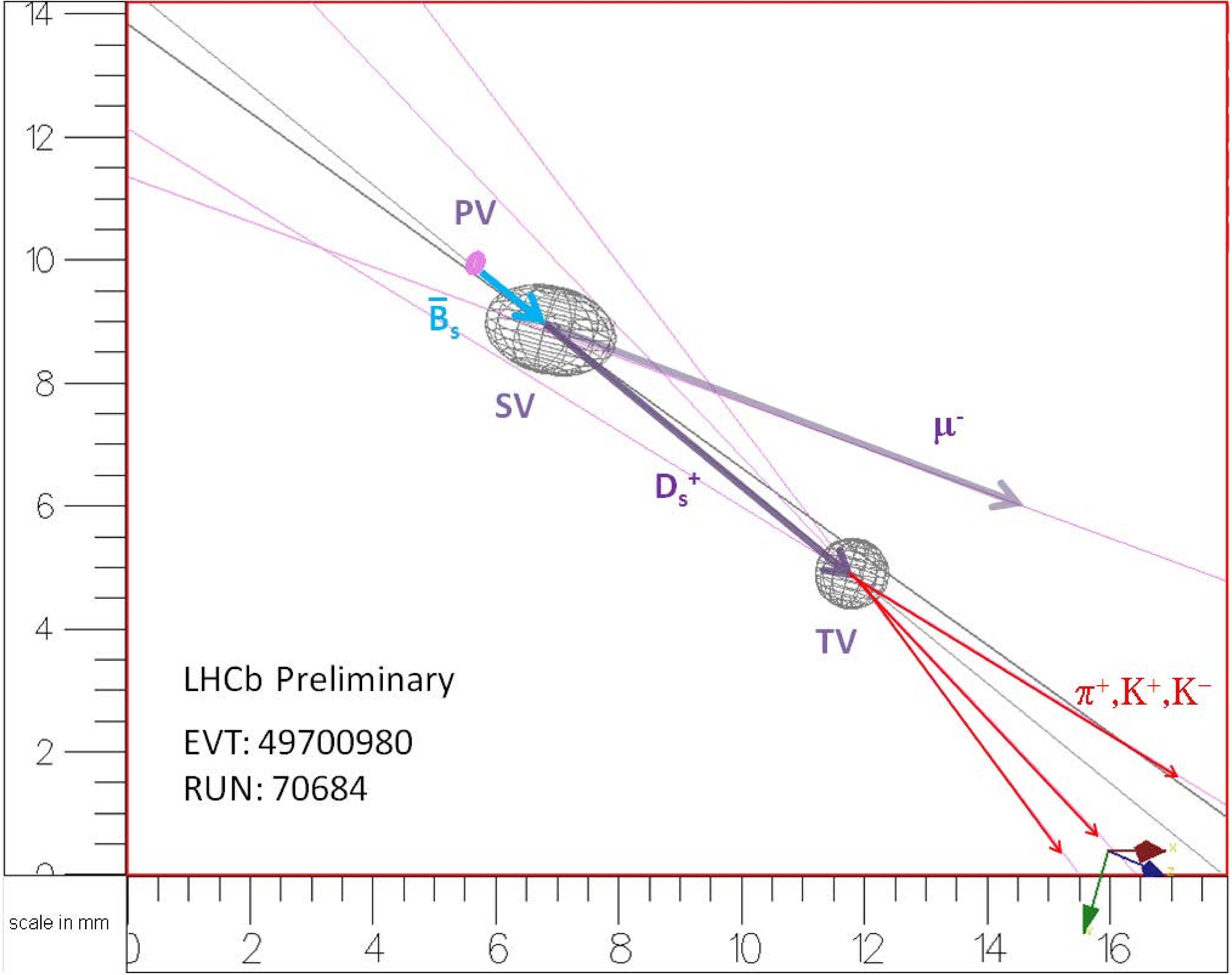
would be profoundly changed

Much more to learn …

Revolution: the meaning of identity

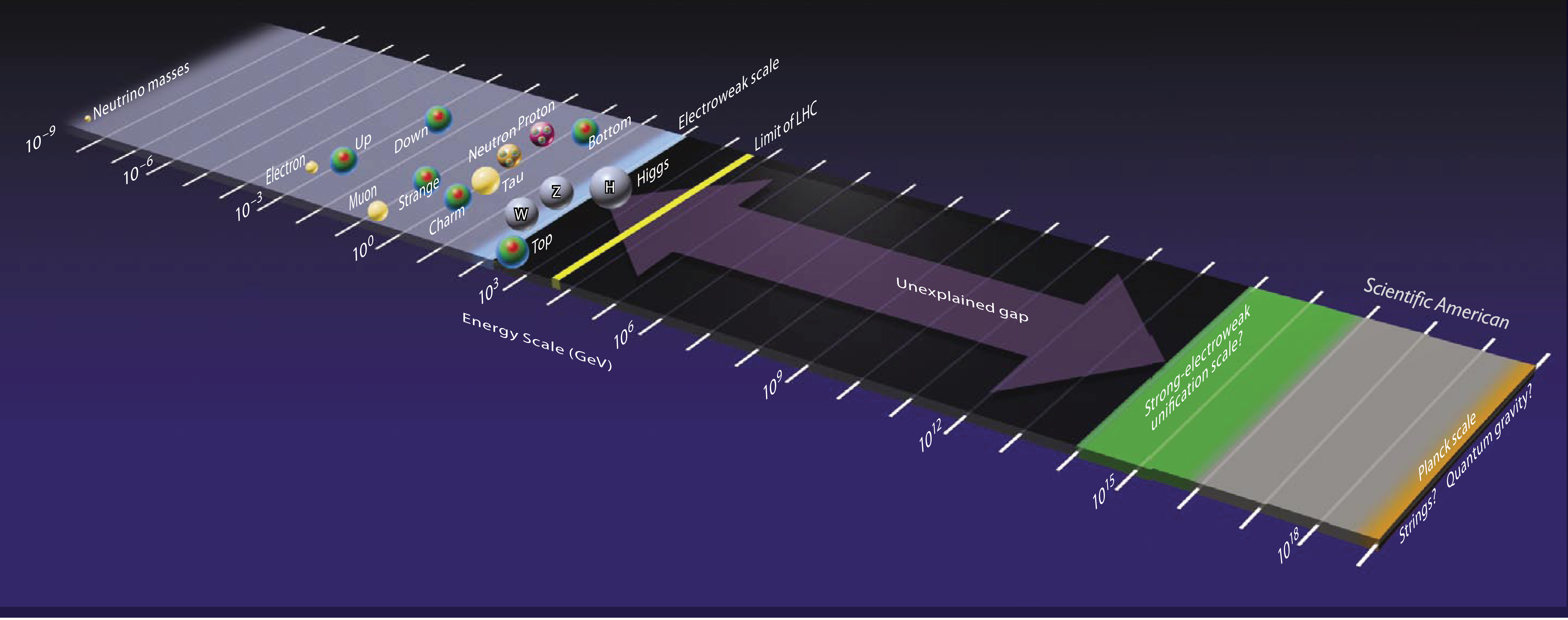
- What makes a top quark a top quark and an electron an electron?
- What sets masses of quarks & leptons?

top quark weighs 300,000 x electron



PV
$\overline{B}_s$
SV
μ^-
D_s^+
TV
π^+, K^+, K^-
LHCb Preliminary
EVT: 49700980
RUN: 70684
scale in mm

An electroweak puzzle:
Does M_H < 1 TeV make sense?
The peril of quantum corrections



How to separate electroweak, higher scales?

Extend electroweak theory on the 1-TeV scale …

composite Higgs boson

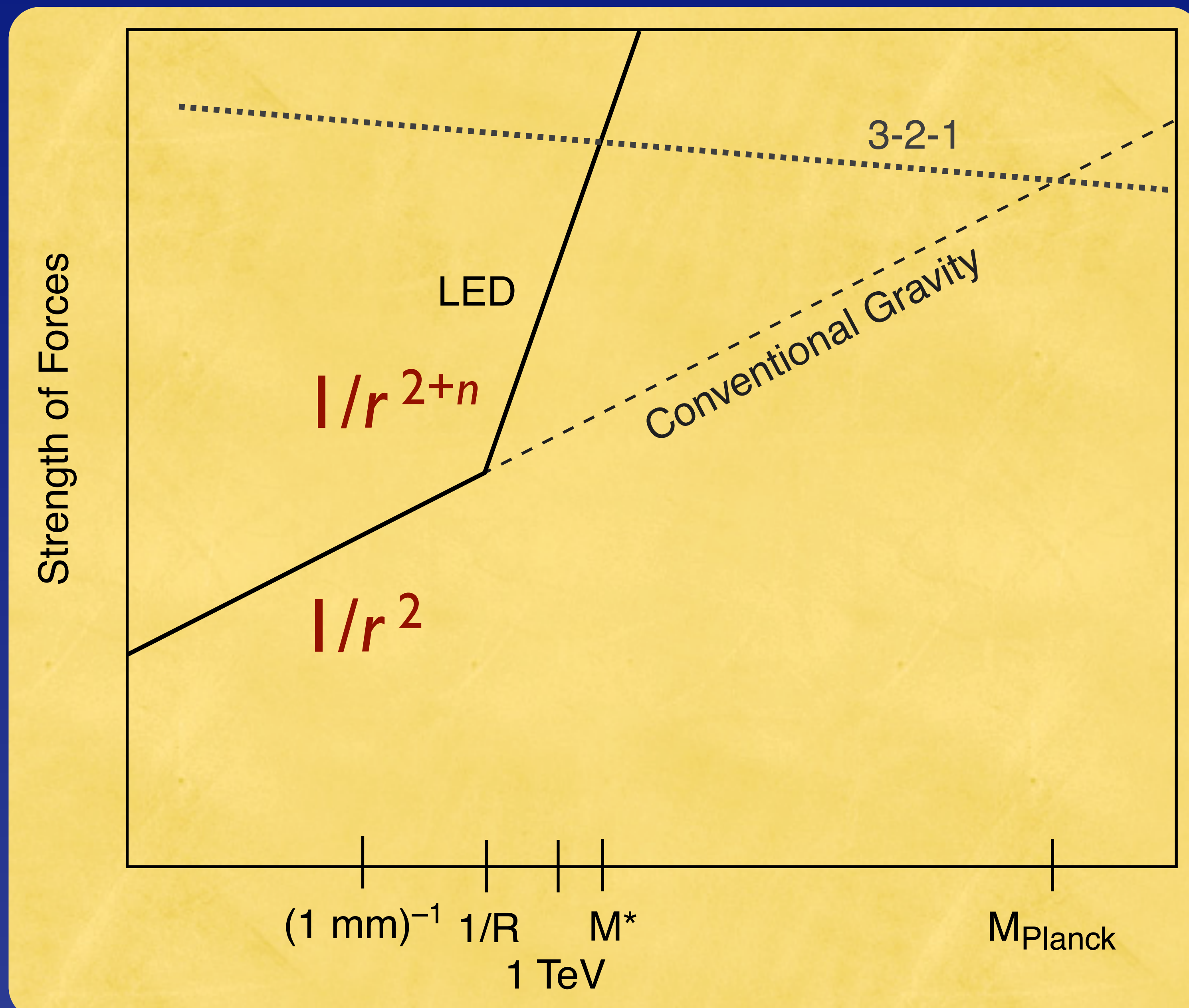
technicolor / topcolor

supersymmetry

…

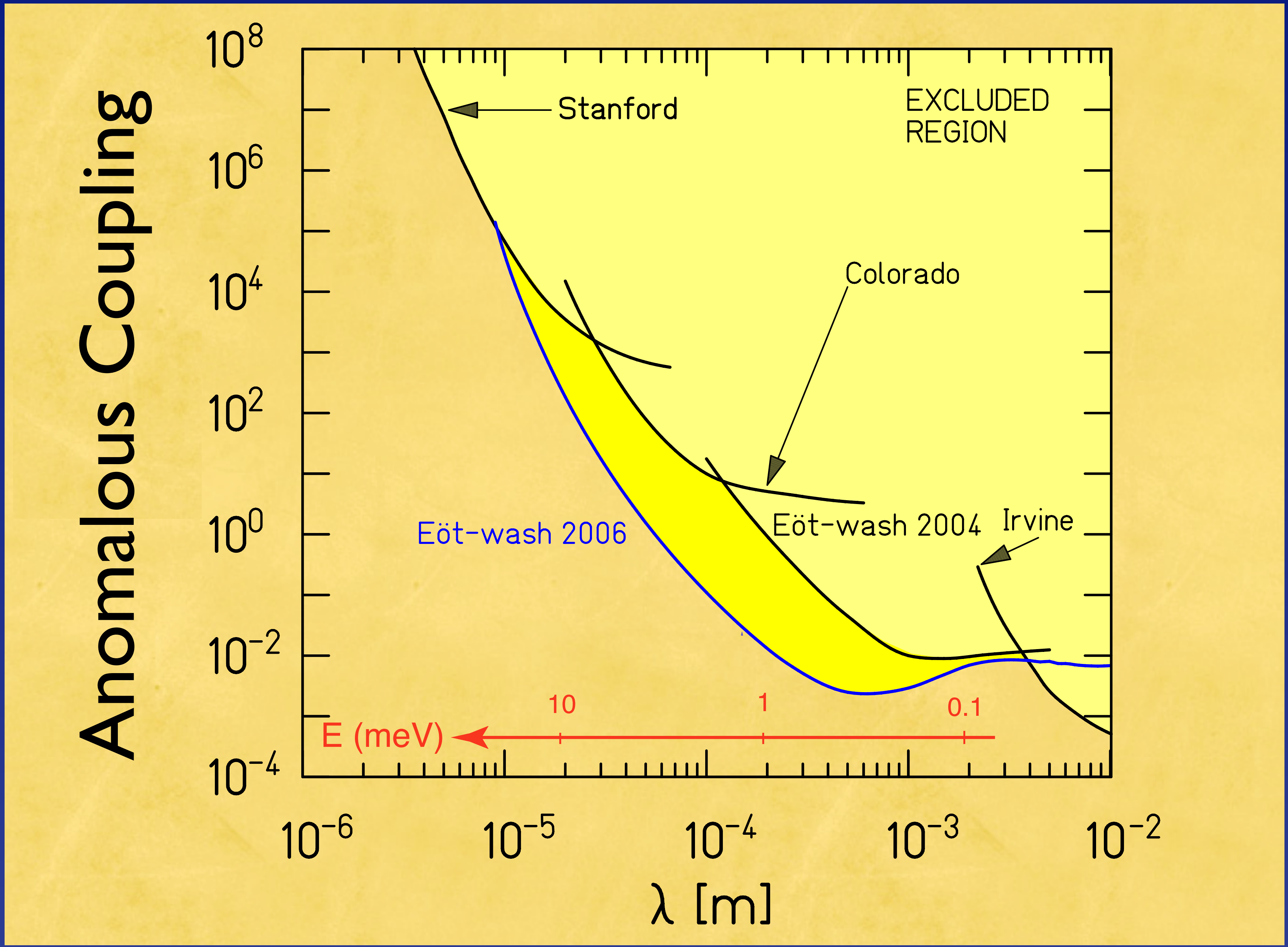
Ask instead why gravity is so weak

Suppose at scale *R* … gravity infiltrates 4+*n* dimensions



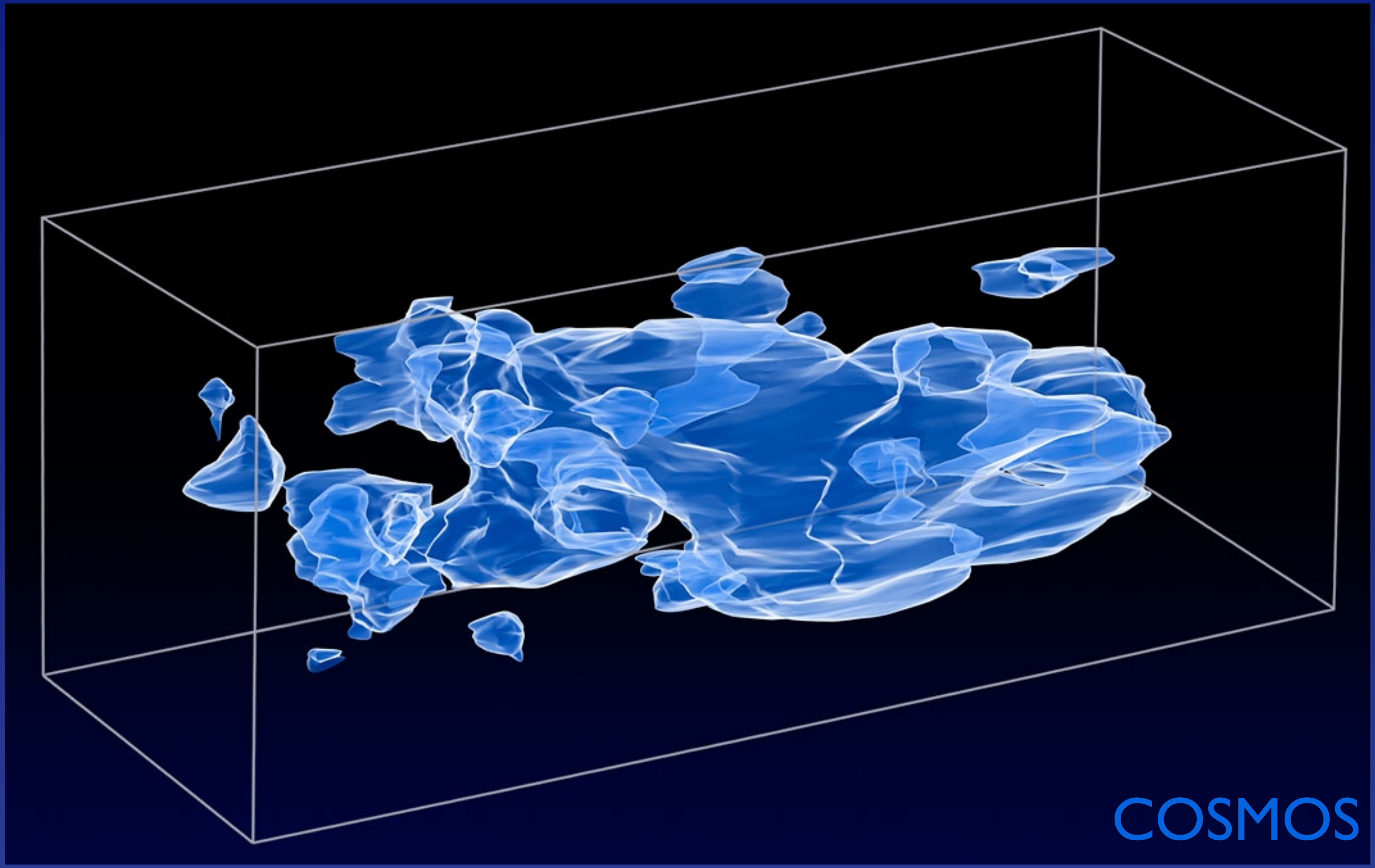
M_{Planck} would be a mirage!

Gravity follows Newtonian force law down to ≲ 1 mm



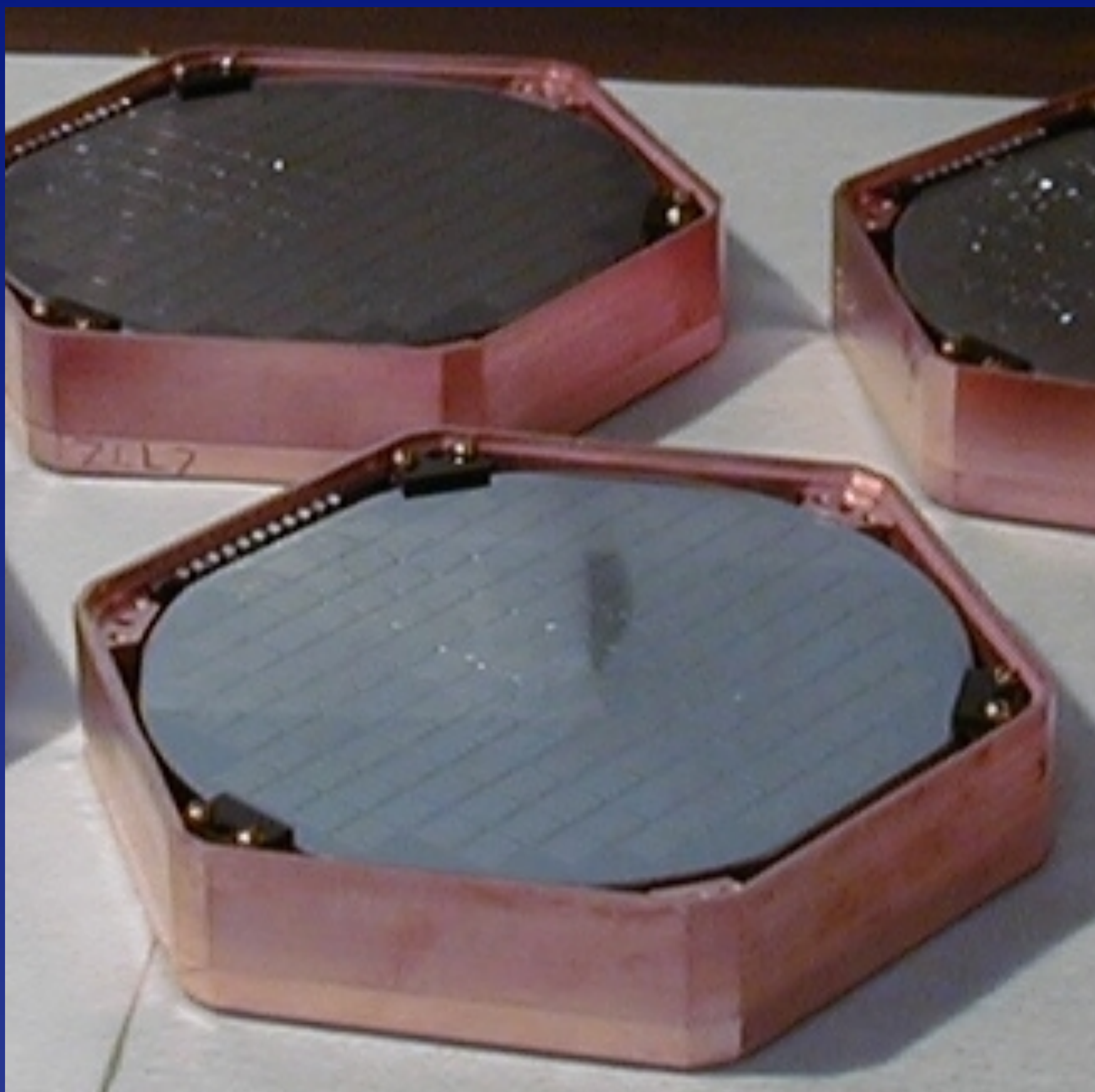
More New physics in the LHC range?

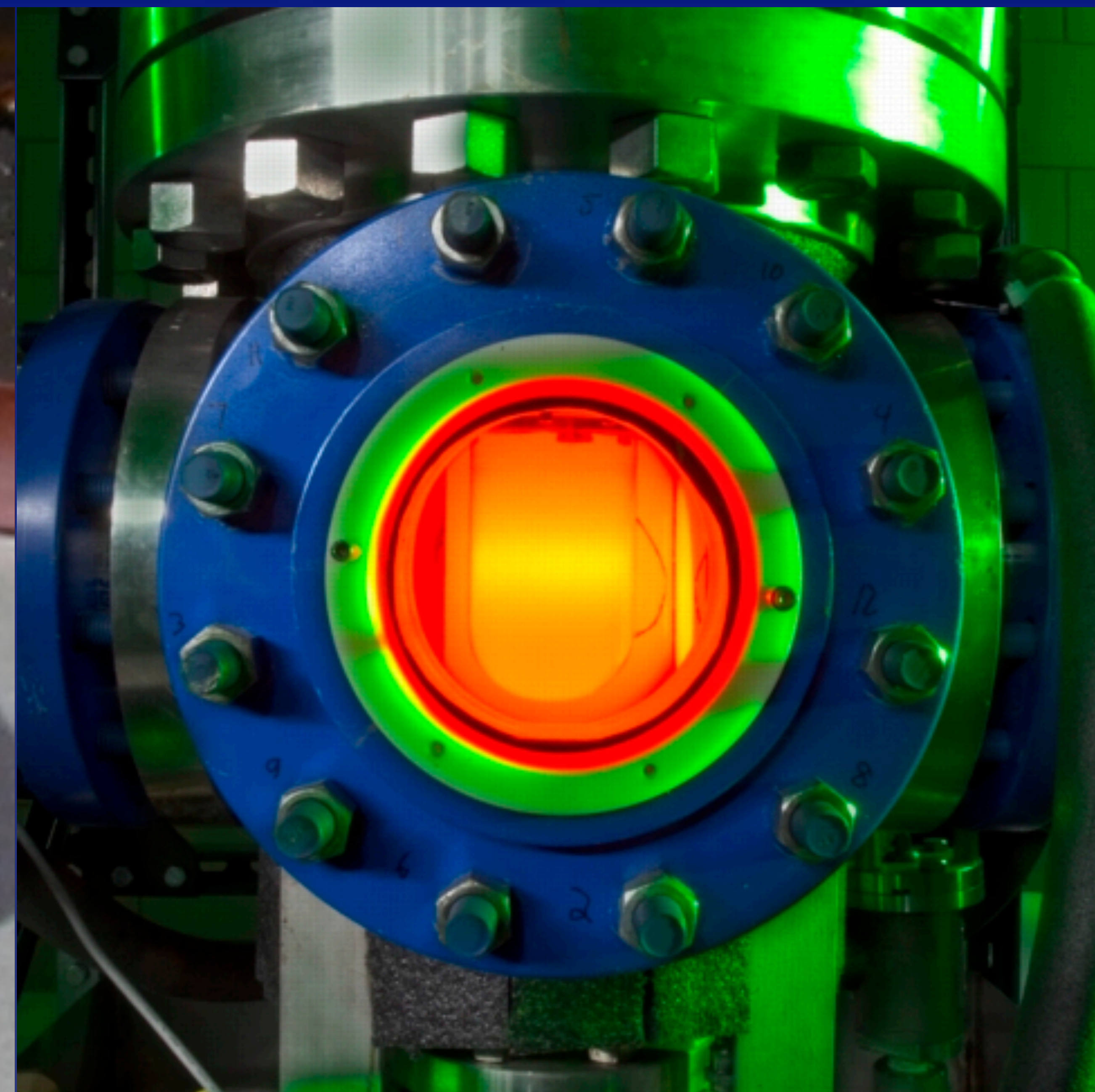
If dark matter interacts weakly …



… its likely mass is 0.1 to 1 TeV

Dark matter relics of the big bang?





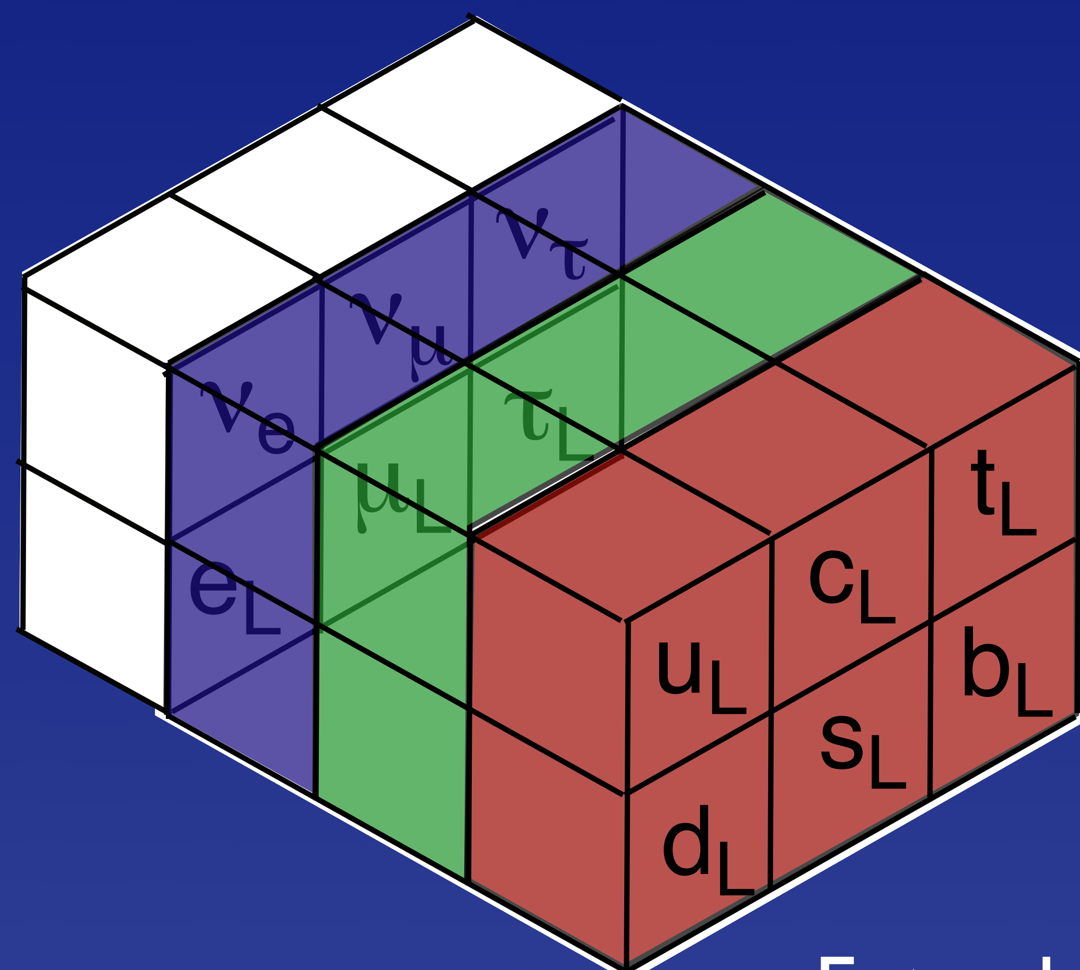
Revolution:
Unity of Quarks & Leptons

- What do quarks and leptons have in common?
- Why are atoms neutral?

Conjectured Law of Nature?

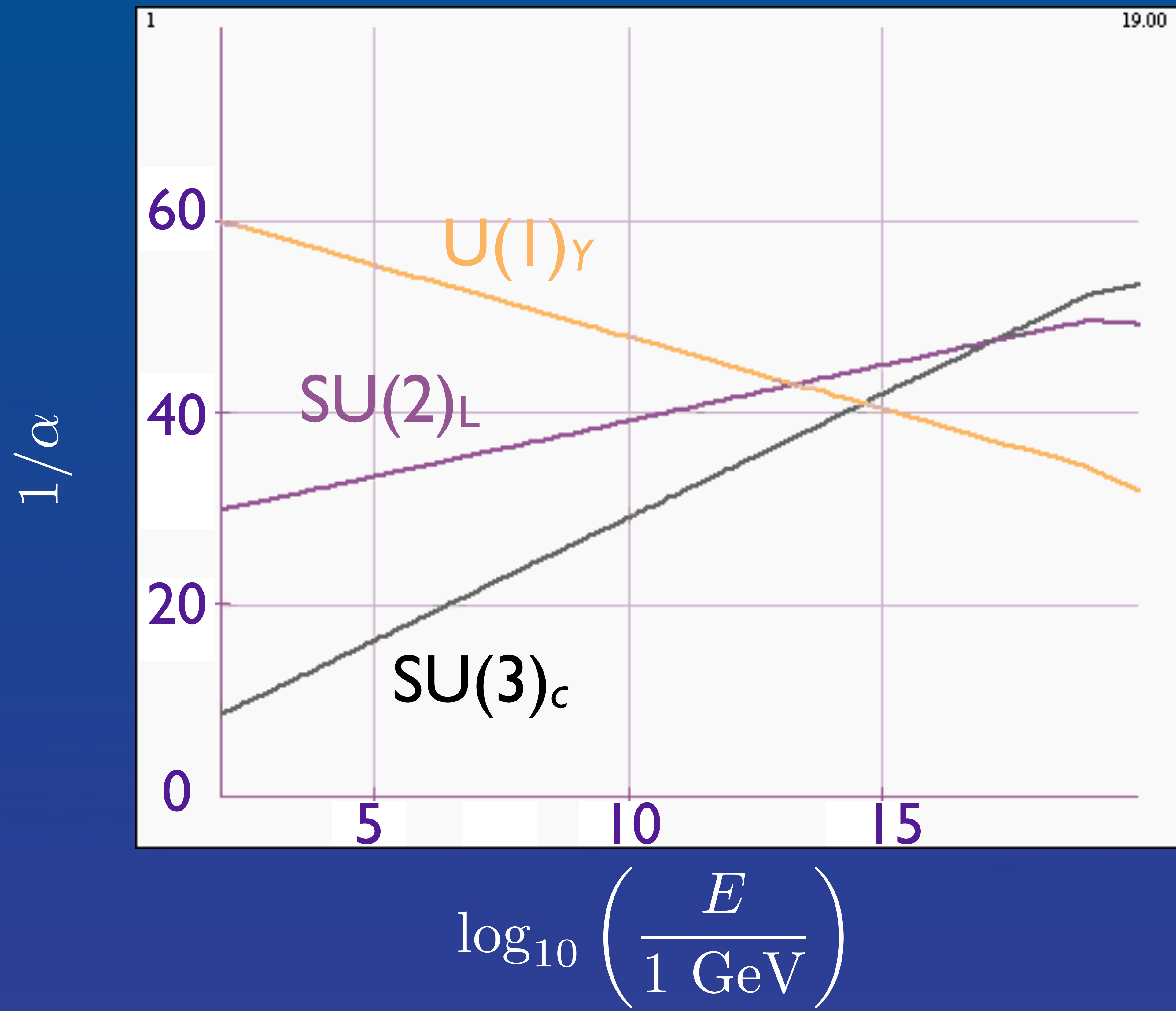
A symmetry among quarks and leptons …

… would have to be a hidden symmetry

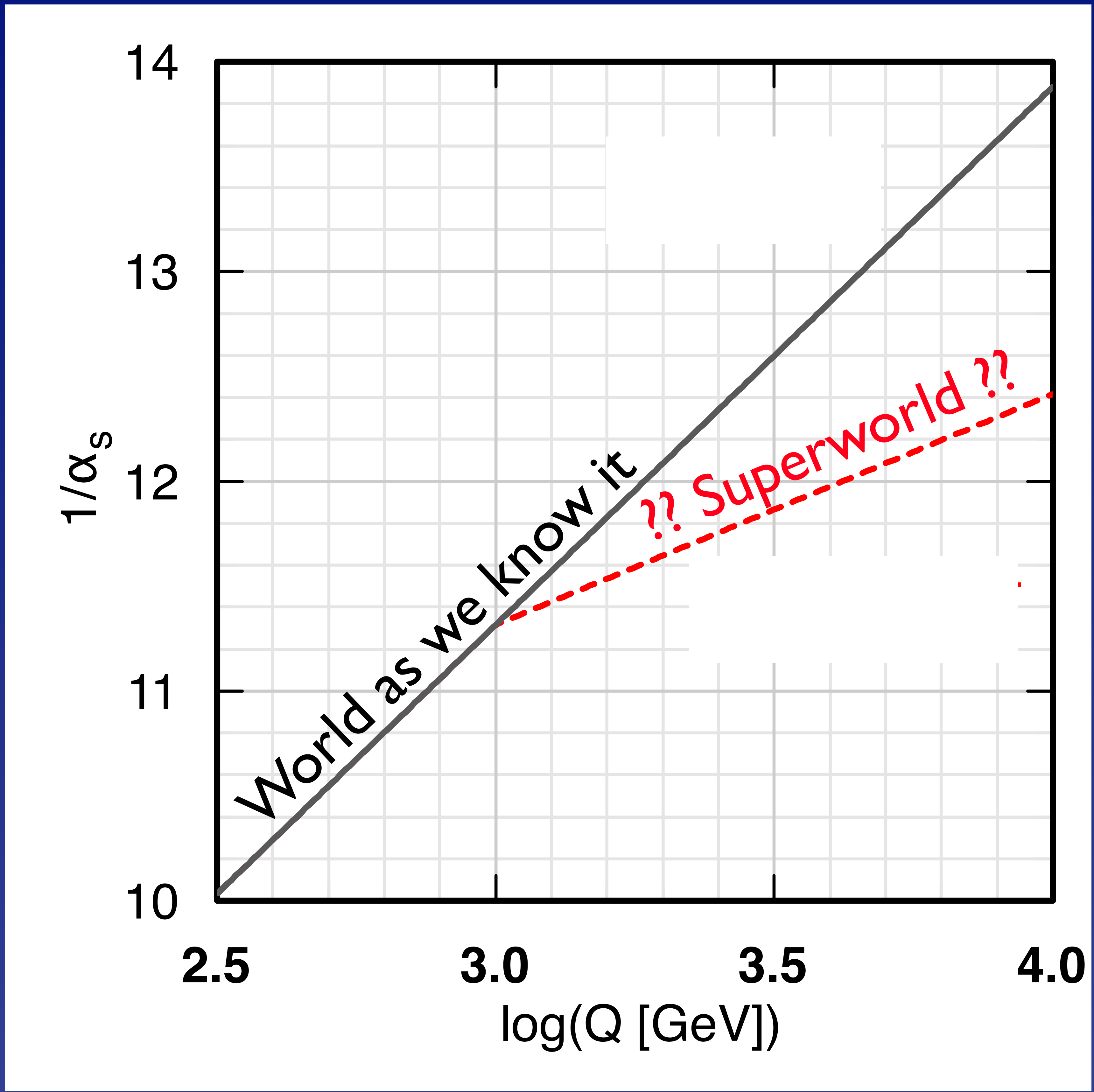


Extended quark–lepton families:
proton decay!

Unification of Forces?

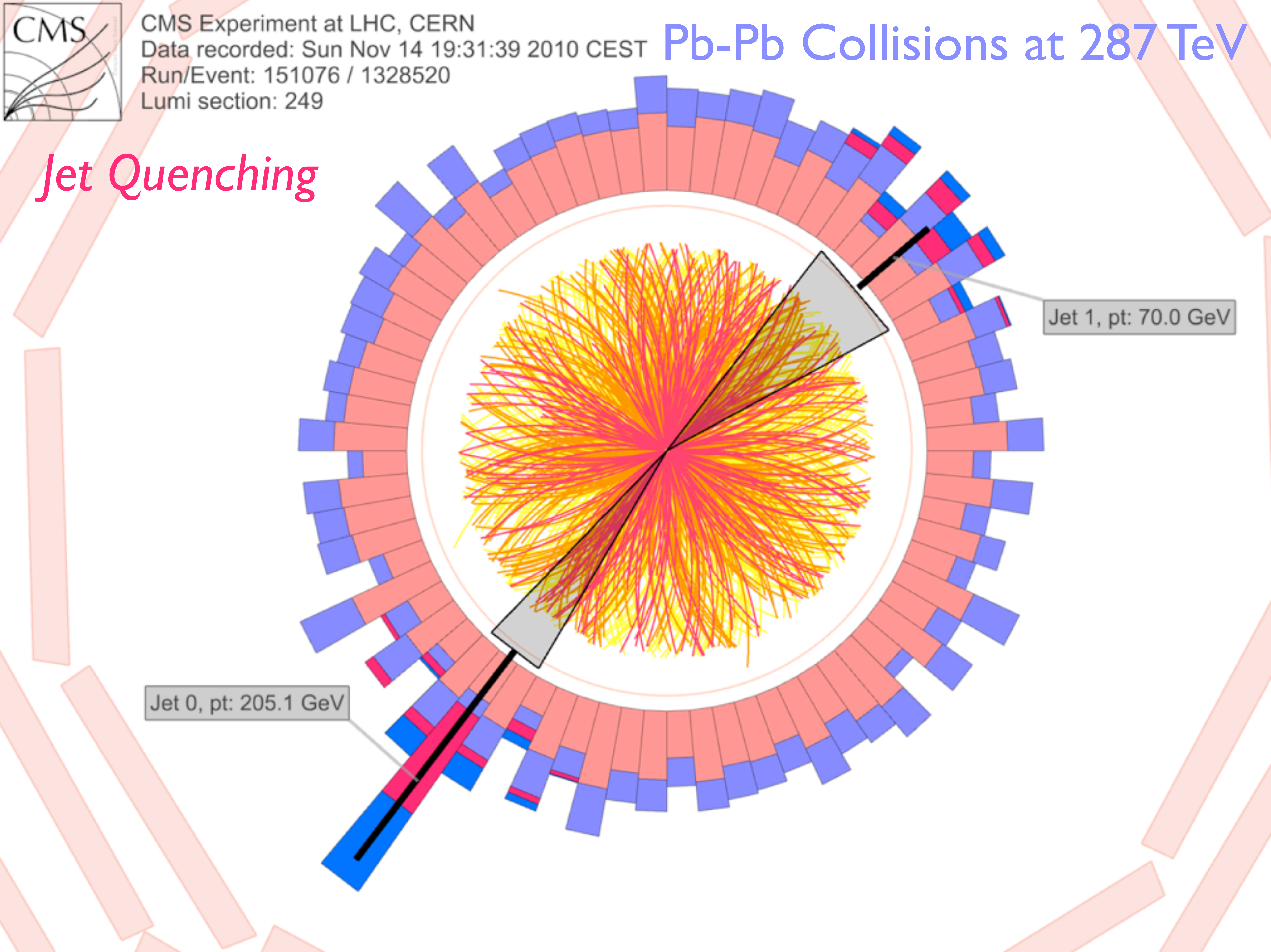


Might CMS see the strong interaction change?



Pb-Pb Collisions at 287 TeV

Jet Quenching



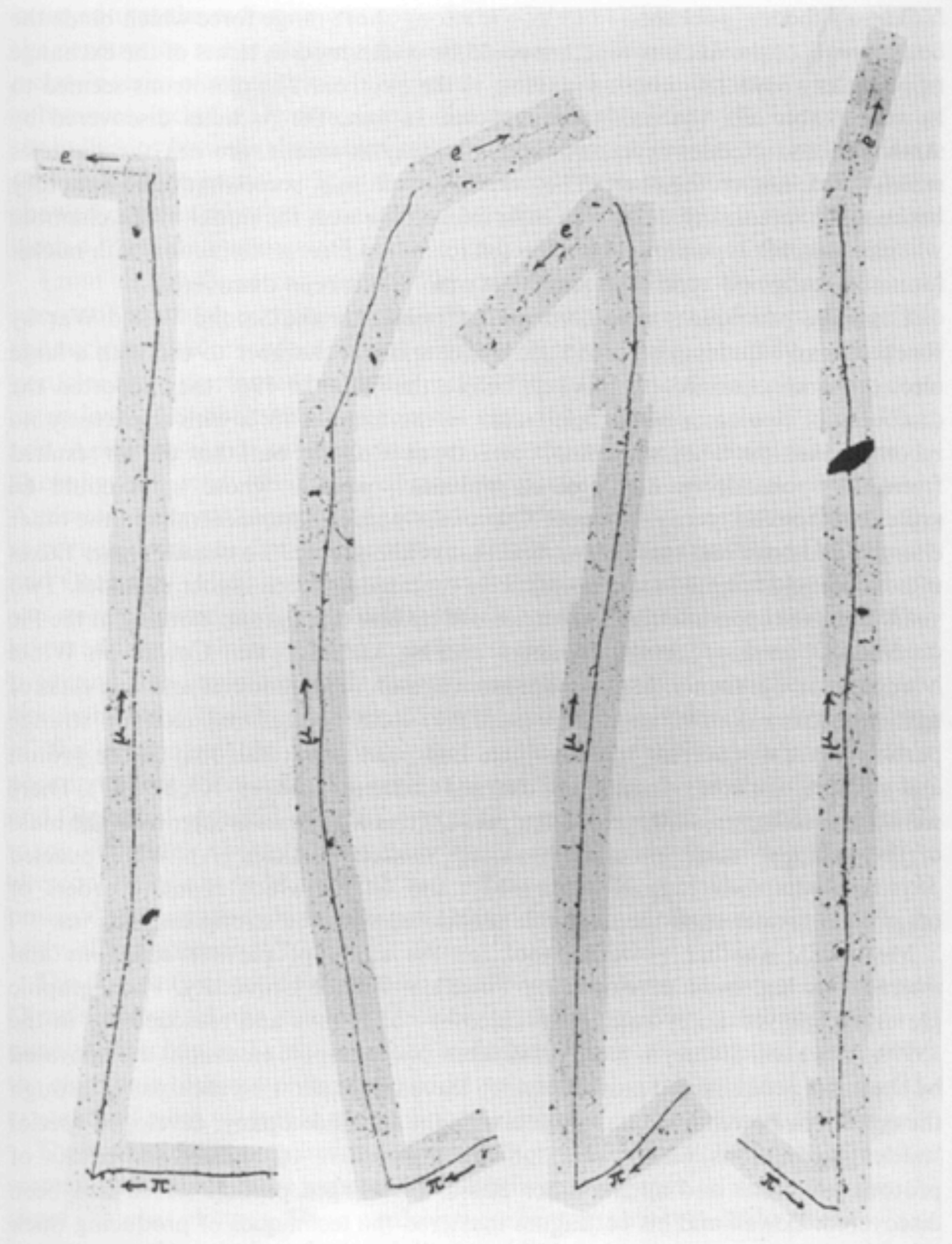
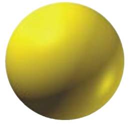


Figure 1.6. Four examples of the decay of a pion into a muon, followed by the subsequent decay of the muon into an electron. These processes were discovered by Powell and his collaborators using nuclear emulsions. (From C. F. Powell, P. H. Fowler and D. H. Perkins (1959). *The study of elementary particles by the photographic method*, page 245, Plate 8-5, Oxford: Pergamon Press.)

"It was as if, suddenly, we had broken into a walled orchard, where protected trees had flourished and all kinds of exotic fruits had ripened in great profusion."

— Cecil Powell
1950 Nobel Prize

?



THE COMING REVOLUTIONS IN PARTICLE PHYSICS

The current Standard Model of particle physics begins to unravel when probed much beyond the range of current particle accelerators. So no matter what the Large Hadron Collider finds, it is going to take physics into new territory **By Chris Quigg**

KEY CONCEPTS

- The Large Hadron Collider (LHC) is certain to find *something* new and provocative as it presses into unexplored territory.
- The Standard Model of particle physics requires a particle known as the Higgs boson, or a stand-in to play its role, at energies probed by the LHC. The Higgs, in turn, poses deep questions of its own, whose answers should be found in the same energy range.
- These phenomena revolve around the question of symmetry. Symmetries underlie the interactions of the Standard Model but are not always reflected in the operation of the model. Understanding why not is a key question.

—The Editors

When physicists are forced to give a single-word answer to the question of why we are building the Large Hadron Collider (LHC), we usually reply "Higgs." The Higgs particle—the last remaining undiscovered piece of our current theory of matter—is the marquee attraction. But the full story is much more interesting. The new collider provides the greatest leap in capability of any instrument in the history of particle physics. We do not know what it will find, but the discoveries we make and the new puzzles we encounter are certain to change the face of particle physics and to echo through neighboring sciences.

In this new world, we expect to learn what distinguishes two of the forces of nature—electromagnetism and the weak interactions—with broad implications for our conception of the everyday world. We will gain a new understanding of simple and profound questions: Why are there atoms? Why chemistry? What makes stable structures possible?

The search for the Higgs particle is a pivotal step, but only the first step. Beyond it lie phenomena that may clarify why gravity is so much weaker than the other forces of nature and that could reveal what the unknown dark matter that fills the universe is. Even deeper lies the prospect of insights into the different forms of matter, the unity of outwardly distinct particle categories and the nature of spacetime. The questions in play all seem linked to one another and to the knot of problems that motivated the prediction of the Higgs particle to begin with. The LHC will help us refine these questions and will set us on the road to answering them.

The Matter at Hand

What physicists call the "Standard Model" of particle physics, to indicate that it is still a work in progress, can explain much about the known world. The main elements of the Standard Model fell into place during the heady days of the 1970s and 1980s, when waves of landmark experimental discoveries engaged emerging theoretical ideas in productive conversation. Many particle physicists look on the past 15 years as an era of consolidation in contrast to the ferment of earlier decades. Yet even as the Standard Model has gained ever more experimental support, a growing list of phenomena lies outside its purview, and new theoretical ideas have expanded our conception of what a richer and more comprehensive worldview might look like. Taken together, the continuing progress in experiment and theory point to a very lively decade ahead. Perhaps we will look back and see that revolution had been brewing all along.

Our current conception of matter comprises two main particle categories, quarks and leptons, together with three of the four known fundamental forces, electromagnetism and the strong and weak interactions [*see box on page 48*]. Gravity is, for the moment, left to the side. Quarks, which make up protons and neutrons, generate and feel all three forces. Leptons, the best known of which is the electron, are immune to the strong force. What distinguishes these two categories is a property akin to electric charge, called color. (This name is metaphorical; it has nothing to do with ordinary colors.) Quarks have color, and leptons do not.

The guiding principle of the Standard Model

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